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ECLSS Advanced Automation Preliminary Requirements -Final Report

Prepared for

Brandon S. Dewberry

Information and Electronic Systems Lab
Software and Data Management Division
Systems Software Branch
Marshall Space Flight Center

Prepared by

Brenda D. Lukefahr
Daniel M. Rochowiak
Brian L. Benson
John S. Rogers
James W. McKee

The Johnson Research Center
The University of Alabama in Huntsville
Huntsville, Alabama 35899

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1.0 PURPOSE

The Environmental Control and Life Support System (ECLSS) Advanced Automation Project has three primary tasks to: 1) determine which software processes in the ECLSS are prime candidates for expert system technology, 2) determine the strategies necessary for developing and integrating these systems into the ECLSS project, and 3) develop expert systems for the ECLSS domain, and demonstrate their value and integrability.[3] The University of Alabama in Huntsville (UAH) is the prime contractor for the initial requirements generation phase (Phase I) of the ECLSS Advanced Automation Project. The objectives of this contract are to:

1) Use "divergent thinking" in reviewing the baselined ECLSS and reviewing successful related expert system approaches to generate a descriptive list of expert system candidates,
2) Evaluate the expert system candidates using specific criteria,
3) Using the requirements of the expert system candidates and knowledge of the baseline ECLSS software and hardware architecture, develop a software hooks and hardware scars list for future implementation of the expert system candidates, and
4) In parallel, develop a potable water recovery FDIR manager in order to drive requirements and to show a proof of concept demonstration.

In fulfilling this purpose, we have prepared this report, UAH Research Report No. 823 which is the final report of the "ECLSS Advanced Automation Preliminary Requirements", and a second UAH Research Report No 824 titled "A Diagnostic Prototype of the Potable Water Subsystem of the Space Station Freedom ECLSS."[115]

In this document, a description of the total ECLSS system has been pulled together from the available publications on ECLSS and Advanced Automation. The description of the hardware is presented in a top down format, the lowest level of which is a functional description of each candidate inplementation. For each candidate implementation both its advantages and disadvantages are presented. From this knowledge it has been suggested where expert systems could be used in the diagnosis and control of specific portions of the ECLSS. A process to determine if expert systems are applicable has been presented, and where applicable, how to select the expert system. A section on "Concerns" has been included which describes the consideration of possible problems or inconsistences in the knowledge or workings of the subsystems. An annotated bibliography of these publications is presented in Appendix A. Finally this report presents in Appendix C the Hooks and Scars Document and in Appendix D a dictionary of the acronyms and terms used in ECLSS. An index is included for ease of reference.

2.0 CONCERNS

In this section we present some concerns and observations that have resulted from our examining the ECLSS system from an overall system viewpoint.

2.1 Concerns Regarding System Hardware

It is very difficult to provide expert fault diagnosis for a that is still in design. Only a limited amount of test data exists and expertise is spread over many vendors and subsystem designers. For example, no test team has had a chance to evaluate the prototype potable loop hardware in an integrated configuration for an extended period. The phase III Core Module Integration Facility (CMIF) testing is just beginning. Other components of Space Station ECLSS are in similar condition of development. Without such data and expertise about a specific configuration and set of technologies, expert systems development must proceed with computer models for generating simulated "test" data. ECLSS Systems are complex, and while still under development,they are incompletely defined. This proof of concept study illustrates the parallel development of KBS software and system hardware, that is necessary for the efficient and successful implementation to proceed.

There will always be compromises in any design project. Certain trade-offs in launch weight versas system complexity and versatility will be inevitable. One such design trade-off is of special concern for knowledge based system application. The ability of a KBS to detect and diagnose faults is directly related to the number and complexity of the sensors which supply the KBS with data. It may be unreasonable to propose that instrumentation sufficient to automatically diagnose all possible faults be included in designs. The weight, power and added system complexity may be a poor trade for the relatively small amount of crew time saved by such a system. Conversely, minimal instrumentation would limit KBS diagnostic solutions to more simple cases. If KBS applications for the Space Station Freedom are to be successful, some attention must be given to the type, number, and location of sensors throughout the design process. This will allow the KBS to diagnose a significant number of faults with the associated savings in crew time, without severe weight, power, and system complexity problems associated with "over instrumentation".

Development work should be directed toward producing more stable sensors with self check and auto-calibration capability. A quite ingenious sensor for O_2 partial pressure has been developed for use in the Atmospheric Control and Supply (ACS) subsystem [76]. Similar sensors for pH and conductivity should also be developed or KBS diagnostics may produce messages such as "check pH sensor #12 calibration". Monitoring possible system contamination by microorganisms should be a thrust area in sensor development. Current conventional microbial assays are too slow (hours to days) to control such a small scale reclamation system. By the time

some these conventional analyses are complete, the system may be profoundly contaminated and require a substantial amount of crew time to disinfect and restart. In the absence of some form of near real time monitoring, a KBS can only alert the crew to process conditions which "might" lead to microbial contamination, such as low temperatures in a heat exchanger/sterilizer or inadequate iodine residual. These conditions may or may not result in increased microbial populations. Also, a system operating within specifications with regard to chemical and physical parameters may experience a microbial population increase. Without any form of automated microbial monitoring KBS diagnosis is severely limited to issuing warnings when microbial control systems are operating outside optimal levels.

Organic contaminant monitoring is another area where additional development may be beneficial. Astro has produced a UV absorbance monitor which provides a continuous measurement of some types of organics. This instrument has several advantages over conventional oxidation/ IR absorbance instruments which only operate in batch mode and require aggressive reagents. However, many organic compounds including many which are toxic do not absorb in the UV region. In addition, these monitors are only useful for low level (ppb) measurements. A multiple wavelength instrument using a photodiode array detector might be capable of determining more accurately the particular classes of contaminants present. Likewise, new developments in surface acoustic wave detectors might also prove to be effective monitors for difficult classes of organic contaminants.

2.2 Documentation

During the project we have examined a great deal of the available documentation for ECLSS. Unfortunately, this process has proved to be inefficient. What is needed is a central index to all of the documents about the system, the latest updates to the documents, documents that are no longer usable, etc. In short a full text database that is available and on-line is needed. Most publications are composed on a computer. The word processing or document processing software can generate both plain ASCII files and indexes. A large computer network with appropriate software should be able to use this and assemble a database. The database should include both published reports and internal NASA reports. A separate section should be set aside for news and presentations. At a higher level of functionality, the database could incorporate hypertext browsing links. Such links would allow the user to move among the documents in terms of the context of the document being browsed, thus coordinating the distributed information.

Without a documentation database a great deal of time and money is put into locating documents, finding related documents, actually securing the document, reproducing the document,

reading around the document to find the information, etc. In the end much effort is wasted since it either duplicates information in other documents, or is simply out of date. Improving the efficiency with such a documentation database would be of great value in knowledge acquisition, knowledge management, and design knowledge capture.

2.3 Knowledge Management

In building any sort of system, whether it is a traditional system or an expert system, the knowledge that is incorporated into the system must be managed. The management of the knowledge is a difficult task, but one that technical writers and documentation specialists have had to deal with for many years. The resources of these individuals should be solicited in building a knowledge management system.

A knowledge management system is a system that allows access to representations of knowledge and provides for the updating of that information. The development of standard templates for items that can be conceptually represented as frame, scripts, rules, flow charts, etc would serve to ensure the ability to gain access to knowledge that is needed in the development of any system, but especially a knowledge based system. The knowledge representations that are managed by such a system would form a basic template for others working on similar or connected knowledge structures.

Without such a system, knowledge acquisition may remain an idiosyncratic and solitary process. This would still be true even if automated tools were used for knowledge acquisition. If the knowledge cannot be put into a common representational scheme, then it will be idiosyncratic. If the knowledge cannot be shared, then it will remain with the individual. The benefits of development of a knowledge management system are that any individual can use any tools that he or she likes just so long as it produces representations that can be added to the knowledge base, the use of a knowledge management system will encourage cooperation among all knowledge acquisition teams, and, finally, the development of a knowledge management system will provide for an effective way of checking the consistency or compatibility of various knowledge driven projects. Ideally, such a system would be tied to the documents base, and this would provide the mechanism for linking the knowledge producers to the knowledge representers.

2.4 Knowledge Tools

The development and ready availability of sophisticated knowledge tools is clearly needed. Object oriented programming, multi-agent systems, blackboards, opportunistic inferencing, and many other conceptual devices are needed if good knowledge based software is to be produced. Without these tools not only is what can be done limited, but that what will be done is to force a system design into a particular style of manipulation that may make it difficult to understand and maintain the system in the future.

The drive for Ada was motivated by these concerns. But even if Ada is the common language for all software, it will not affect the intelligibility and maintainability of the knowledge in the system. Even if CLIPS is rewritten into Ada and if this increases the maintainability and intelligibility of the CLIPS system, it will not increase the maintainability and intelligibility of the knowledge that CLIPS is designed to manipulate.

Much of the work in Artificial Intelligence (AI) is being done on LISP machines. It seems reasonable to think that a special LISP system may be able to address some of the knowledge tasks better than other sorts of systems. It may also be that the tasks might be done more cost effectively on a LISP machine since the cost of converting from a LISP based system to a more traditional system would be avoided.

2.5 The Distributed Database On Space Station

The idea of a distributed database system for the Space Station is a great idea. Unfortunately, one might reasonably predict that the system will become overloaded as everyone developing software seeks to take advantage of it. In ECLSS there is a great deal of information that could conceivably be loaded into the database. This approach would be ideal for facilitating exchange between ECLSS support software and other ECLSS units. However, this approach may also overload the database system, especially if all sensor data is sent to the database, a historical record is kept, and the number of sensors is increased. Thus, some policy governing the use of the database system is needed. Alternatively, the processors and networks can be enhanced.

2.6 Specific Concerns

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2.6 Specific Concerns

It is not completely clear how the subcomponents of the ECLSS will communicate. In particular it seems that the Temperature and Humidity Control (THC) and Water Recovery and Management (WRM) subsystems would need to communicate with each other about what to expect

and what is needed. For example, the Potable Water system may need to know that THC does not anticipate generating the nominal volume of condensate. Another example may be the way in which the products of a fire could affect the operation of the potable system.

It appears that more attention has to be given to the way in which simulations may provide an important "look ahead" in reasoning about the state of the system. One of the things that a simulation might allow is for the anticipation of problems or difficulties.

Attention also needs to be given to the scheduling of human activities. Various human activities can increase the amount of condensate being produced, and the health of the crew can lead to increased demands on the system. Some of these activities if known could be used in an automated planning system. Another issue is the number of crew members. If the number varies over time the system may need human attention at various points. For example, if the number of crew members is over a specified number, it well be necessary to change the unibeds more frequently.

Information concerning the operation and effeciency of the individual unibeds, other than the first unibed was not found. If each bed is assumed to generate the same proportionate effect as the first, unrealistic values are generated. Therefore a more detailed examination of the operational efficiency of multiple unibeds in the multifiltration unit needs to be performed.

It has been difficult to gain an accurate understanding of the ECLSS software since the general philosophy of the ECLSS software context diagrams has not been clearly presented.

It is not clear that the operations on potable and hygiene water are significantly different. If they are not, then it might be good to unify the software for these subsystems in the same way that the water quality software has been unified.

We could not locate any published accounts of what managers and users might want the software for ECLSS to do. An investigation of what the users might want in the way of advanced automation is needed. While it is clear that the users appear to want the routine tasks to be automated, there does not appear to be a clear line between the routine and the unusual.

Also there needs to be a clearer specification of which parts of the ECLSS software will be ground based and which will be station based. This is important since there seems to be no requirement that ground-based software must be in Ada. Thus, ground based software could take advantage of already existing tools. Also this would raise the issues of ground to station communication links, speed, and protocols.These need to be more clearly defined.

Some attention should be given to the various user models to be incorporated in the software. Suppose the crew member who was an ECLSS specialist was injured or ill. Some other crew member would need to fill in. It might be reasonably assumed that this crew member is not as well versed in specific ECLSS operation as the unavailable crew member. If this is so, the

replacement user of the ECLSS software may need a different level of help than the specialist, especially in terms of display that the system generates.

One of the advantages of using standard inference engines, and other standard AI software on the Space Station, is that various updates and refinements to the knowledge components can be sent to the Station and installed on the system. This could be as simple as erasing a file and loading a new one. This, however, would seem to become viable only if there is a specification of the standard software on the Station and the standard knowledge representation schemes used by the software. It is not clear to us what this standard is. To the degree that there is such a standard, it appears that it is given in the structure of CLIPS. This should be clarified.

The criteria for assessing potential advanced automation efforts need to be made more clear. Since the criteria act as a template for generating candidates, these criteria are important and must be clearly defined.

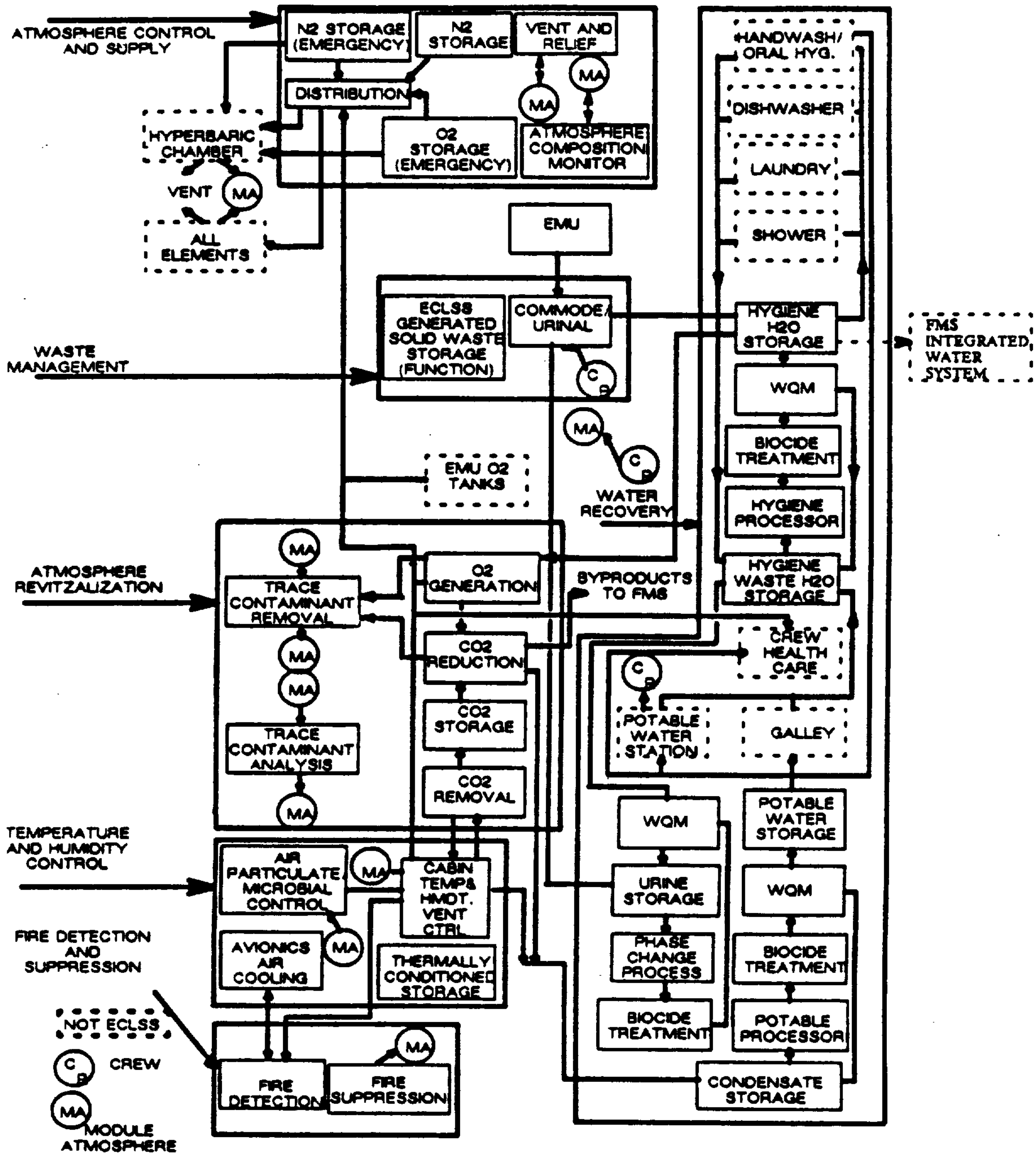
3.0 INTRODUCTION

3.1 ECLSS Science and Technology

The Space Station Freedom's design includes a number of modules, airlocks, and nodes which are docked together to form a pressurized habitat for manned operations. The function of the Environmental Control and Life Support System (ECLSS) is to provide a "shirt sleeve" environment for the crew, as well as providing the water and atmosphere necessary to sustain them.[101] In designing the ECLSS for the manned Assembly Complete (AC) Station the design must include closed loop air and water systems to accommodate the extended duration of the missions and to avoid having to constantly resupply. This is particularly important in light of the fact that Space Station Freedom operations will not have readily available escape capability.[88]

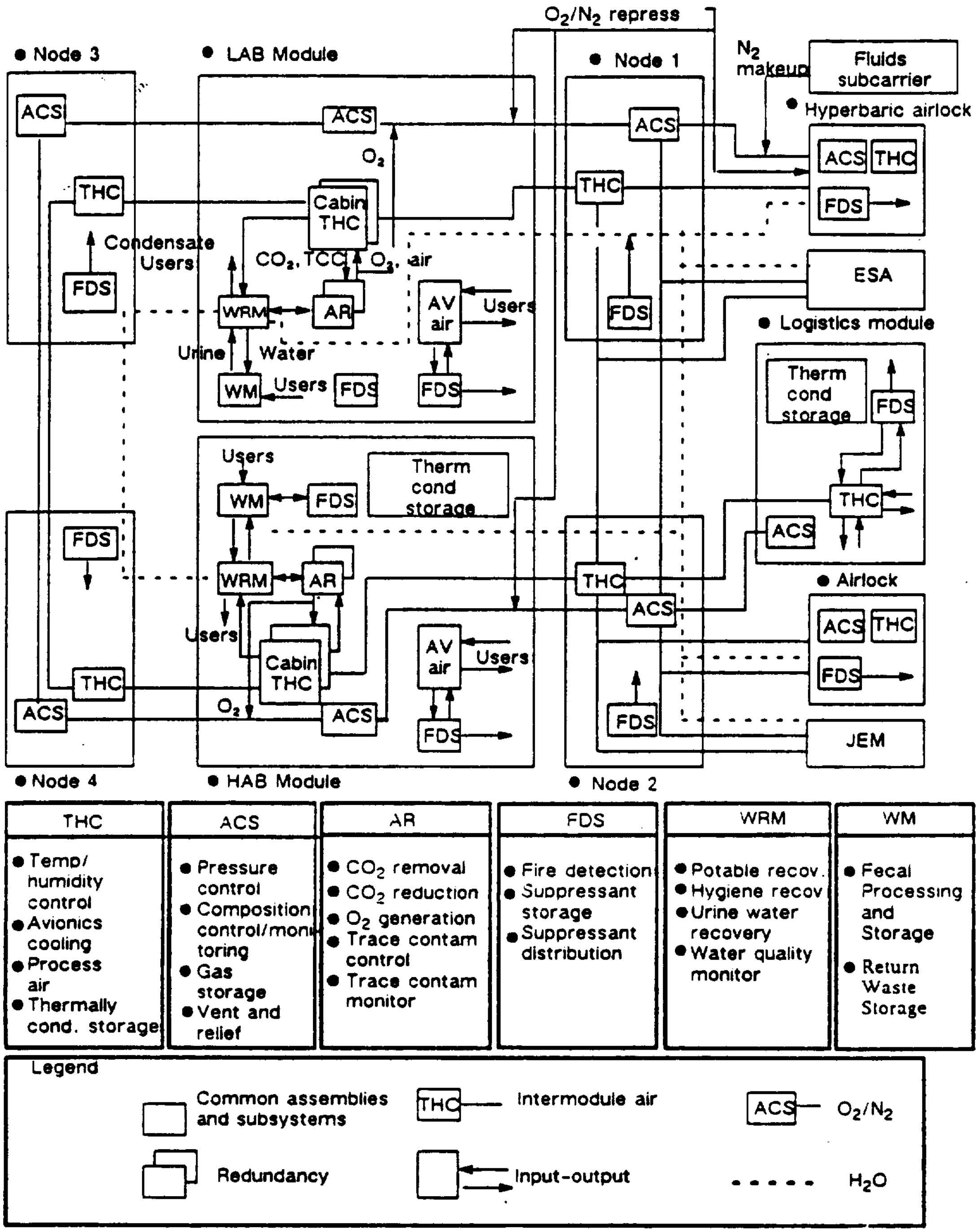
The ECLSS comprises six major subsystem groups, as pictured in Figure 1, which include Temperature and Humidity Control (THC), Atmosphere Control and Supply (ACS), Atmospheric Revitalization (AR), Fire Detection and Suppression (FDS), Water Recovery and Management (WRM), and Waste Management (WM). These subsystems are described in Section II, and their functional interrelationships are summarized in Figure 2.[88]

The hardware/software control architecture is built using components of the Data Management System (DMS). Rack level controllers will control and monitor all the subsystems contained within each ECLSS rack. The element manager controls functions in the elements. The system level controller, partially on-board, partially on the ground, will perform inter-element functions; performance and trend analyses; and system fault detection, isolation, and recovery. It will also interface with the overall station level DMS Operations Management System.[88]



Source: NASA. 1989. "Environmental Control and Life Support System Architectural Control Document," NASA Marshall Space Flight Center, February 15, 1989.[5]

Figure 1. Space Station Environmental Control and Life Support System (ECLSS) Overview.



Source: NASA. 1989. "Environmental Control and Life Support System Architectural Control Document," NASA Marshall Space Flight Center, February 15, 1989.[5]

Figure 2. Environmental Control and Life Support System (ECLSS) Schematic

3.2 ECLSS Information System[29,32]

The software for the ECLSS incorporates several different levels of functionality and processing. This section of the report will focus on the way in which the software leads from the ECLSS Software Support module (now called ECLSSMGR) to the potable water software (POTH2O). No attempt is made in this section to give an exhaustive account of the software for each ECLSS subsystem. However, the discussion of the ECLSS Support Software will apply to all of the subsystems.

ECLSS Support Software (ECLSSMGR)

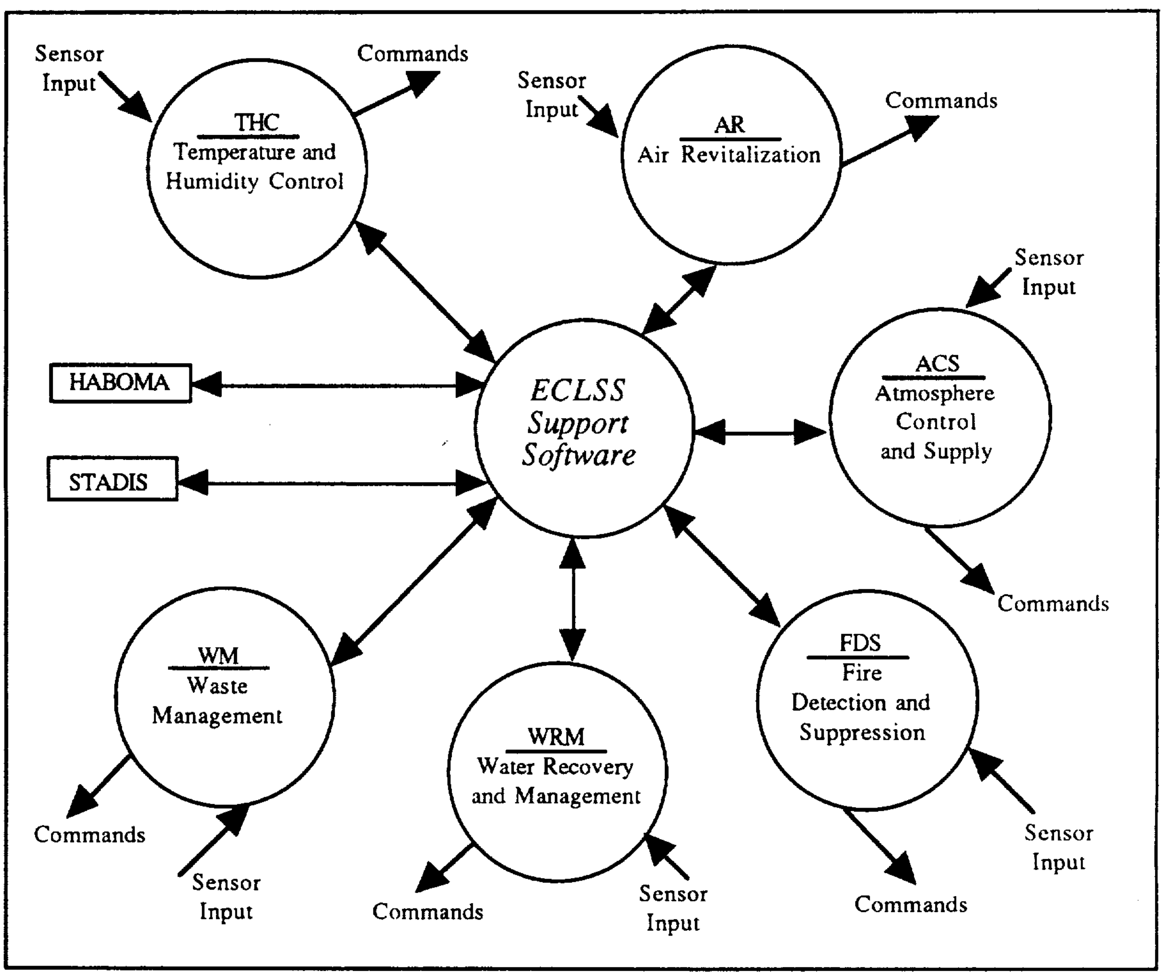


Figure 3. Context Diagram for an Overview of ECLSS Software

The ECLSS Support Software is intended to aid in the administration of the subsystems of the ECLSS. It is through the ECLSS Support Software that the Space Station's HABOMAand STADIS software are informed of the conditions and needs of the ECLSS system. It should be noted that the organization of the software is a logical organization and not a physical organization. It is not a question of where the software is located, but of what the software does. Thus, the software for the subsystems and the ECLSS support software may reside in physically distinct computers, or the same computer.

The context diagram (See Figure 3) indicates the ways in which the ECLSS Support Software (now called ECLSSMGR) coordinates the activities of its subsystems (THC, AR, ACS, FDS, WRM, WM) and passes information to the habitat module level software (HABOMA) and the station level software (STADIS). (Larger context diagrams appear at the end of this report.) Each subsystem of ECLSS is represented in the diagram. At this context level, each subsystem can be thought of as taking in sensor data and, on the basis of its code and communication with the ECLSS Support Software, issuing commands to the hardware. Taken in this way, the software packages for each of the physical ECLSS subsystems represents the actions that ought to take place given certain sensor readings and communication with the ECLSS Support Software. In terms of the context diagram at this

Level	Short Name	Long Name	New Name
Station			
	STADIS	Station Distributed System	
Habitat Module			
	HABOMA	Habitat Operations Management Application	
ECLSS			
	ECLSS Software Support		ECLSSMGR — ECLSS Manager
	THC	Temperature and Humidity Control	
	AR	Air Revitalization	
	ACS	Atmosphere Control and Supply	
	FDS	Fire Detection and Suppression	
	WRM	Water Recovery and Management	
	WM	Waste Management	

level, there is no direct communication of the software for the ECLSS subsystems to the habitat or station level software. Rather it is the ECLSS Support Software that communicates with those software packages. For detailed context diagrams, please refer to Appendix B.

The ECLSS; Support Software receives commands from both HABOMA and STADIS and sends requests and status information to HABOMA while operational data is sent to STADIS. Each subsystem sends requests and status information to the ECLSS Support Software, while the ECLSS Support Software sends commands to the subsystems. In this way, information traverses up and down through the layers of the control software.

Inside of the ECLSS Support Software are six subcomponents that handle the incoming information from the ECLSS subsystems, HABOMA, and STADIS.

Short Name	Long Name
ACTIVATE	Activate Valid ECLSS Process
INHIBIT	Process ECLSS Inhibit Commands
INHDATA ECLSS	Inhibited Function List
CMD	Verify and Validate ECLSS Commands
ECLSSERR	ECLSS Fault Detection and Isolation
ECLSSPER	ECLSS Performance and Trend Analysis
DISPLAY	ECLSS Display

As indicated in the context diagram for the ECLSS Support Software, ACTIVATE is the central subcomponent, since it issues commands to ECLSS subsystems and requests to HABOMA. The commands, however, are checked before an activation. INHIBIT, INHDATA ECLSS, and CMD are the modules that check for processes that are inhibited. ACTIVATE sends a process name to INHIBIT which in turn sends a message to the inhibited function list in INHDATA ECLSS. The resulting process status is sent to CMD. CMD receives requests from all ECLSS subcomponents, as well as commands from HABOMA and STADIS. CMD indicates invalid commands to HABOMA and valid commands to ACTIVATE.

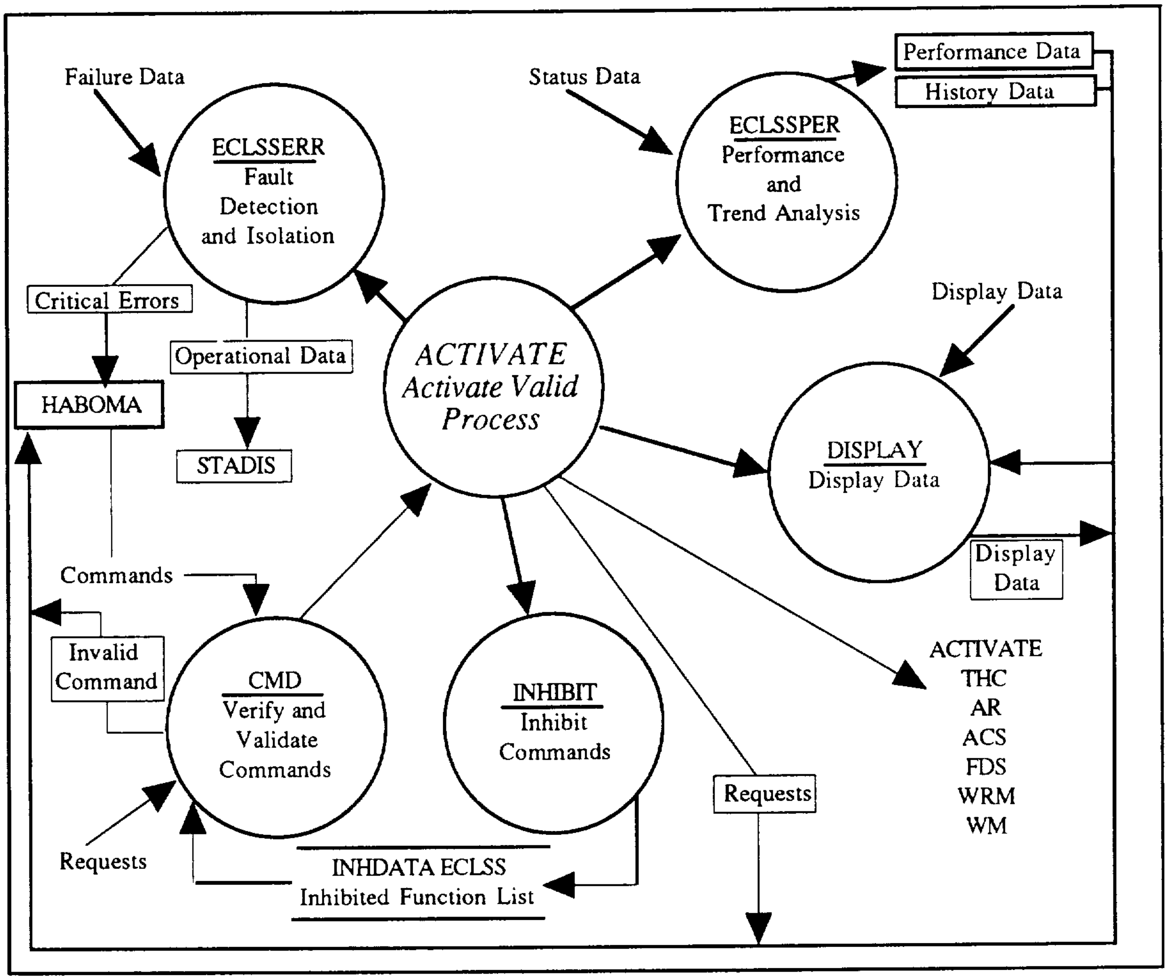


Figure 4. Context Diagram for ECLSS Support Software — ECLSSMGR

ACTIVATE also sends commands to ECLSSERR, ECLSSPER, and DISPLAY. ECLSSERR receives failure data from all ECLSS subsystems and sends critical errors to HABOMA and operational data to STADIS. ECLSSPER receives status data from all ECLSS subsystems and sends history, performance, and status data to HABOMA and DISPLAY. DISPLAY receives display data from all ECLSS subsystems as well as ECLSSPER, and sends display data to HABOMA.

Water Recovery and Management Subsystem (WRM)

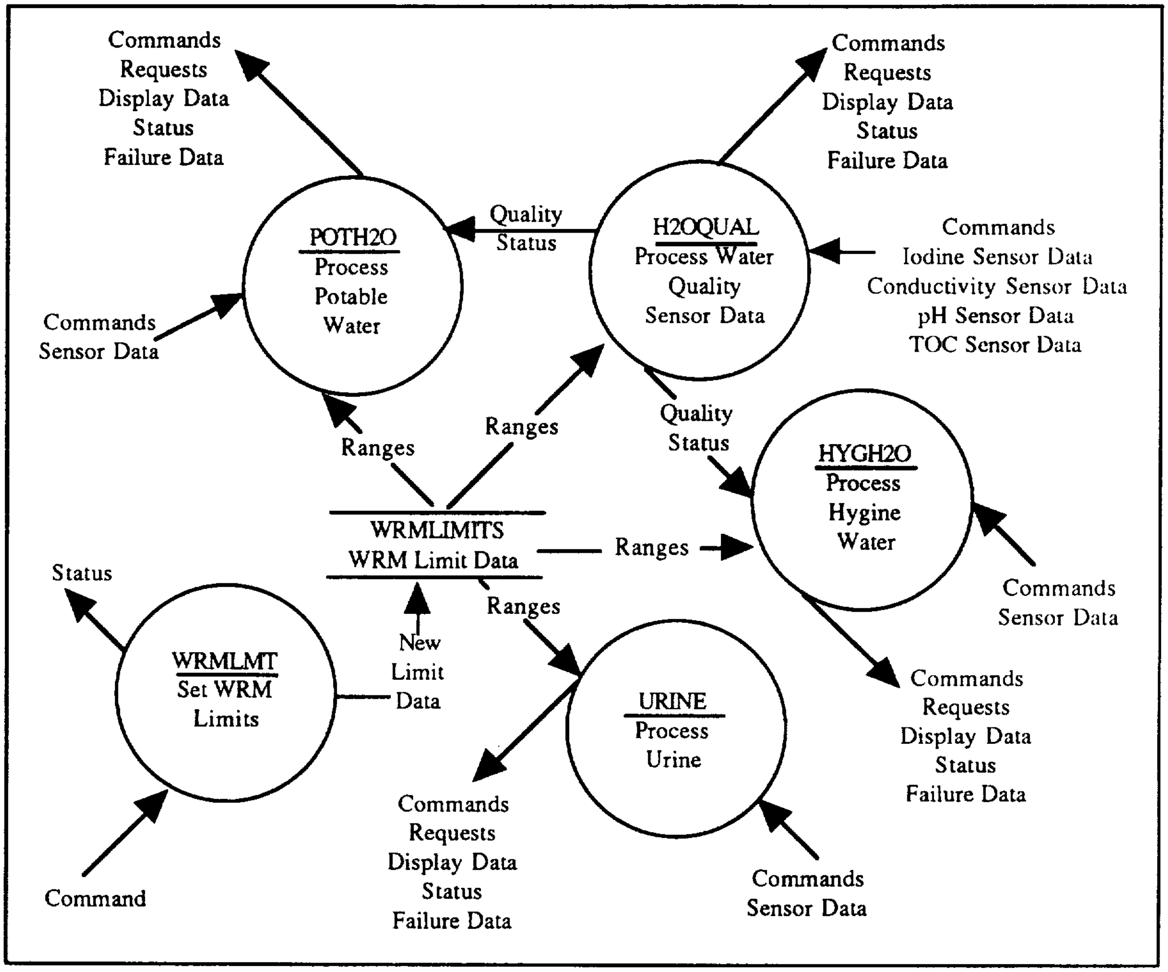


Figure 5. Context Diagram for ECLSS WRM Software

As the context diagram for the WRM indicates there are six modules that include both the potable and hygiene water systems. These modules analyze and control the water recovery functions in terms of the limits set for the subsystem. In general, each unit receives information from sensors and various software units, and on the basis this information processing generates new data and issues commands and requests.

Short Name	Long Name
WRMLMT	Set WRM Limits
WRMLIMITS	WRM Limit Data
POTH2O	Process Potable Water
H2OQUAL	Process Water Quality Sensor Data
HYGH2O	Process Hygiene Water
URINE	Process Urine

On the basis of commands from ACTIVATE, WRMLMT constructs new limit data for WRMLIMITS and reports its status to ECLSSPER. WRMLIMITS establishes the ranges for the main subcomponents POTH2O, H2OQUAL, HYGH2O, and URINE. Each of these subcomponents receives commands from ACTIVATE and sensor inputs from hardware. The case of H2OQUAL is somewhat special since it receives special sensor inputs for iodine, conductivity, pH, and TOC (Total Organic Carbon). Additionally, each subcomponent sends commands to hardware, requests to CMD, display data to DISPLAY, status data to ECLSSPER, and failure data to ECLSSERR. Additionally, H2OQUAL sends quality status to POTH2O and HYGH2O.

Within WRM, POTH2O will be taken as an example since the potable water system is the focus of the demonstration software produced for the overall effort of this research. The details of the demonstration system are presented in UAH Research Report No. 824.[115] It should be noticed, however, that the demonstration software overlaps the functionality of POTH2O and H2OQUAL. In part this is because the physical potable water system overlaps both software components, and in part because the potable water design effort is geared to producing water of a specified quality. This raises the important fact that the breakdown of software components need not match precisely the breakdown of the function of the physical system. In the case at hand there seems to be an obvious reason why the software and physical breakdowns do not correspond. Although the potable and hygiene water systems are distinct physically, the process of monitoring water quality is sufficiently similar that one module (H2OQUAL) can satisfy the demands of both the potable water system (POTH2O) and the hygiene water system (HYGH2O). For reasons of economy, the monitoring process is placed in one module rather than in two and shared by both subsystems.

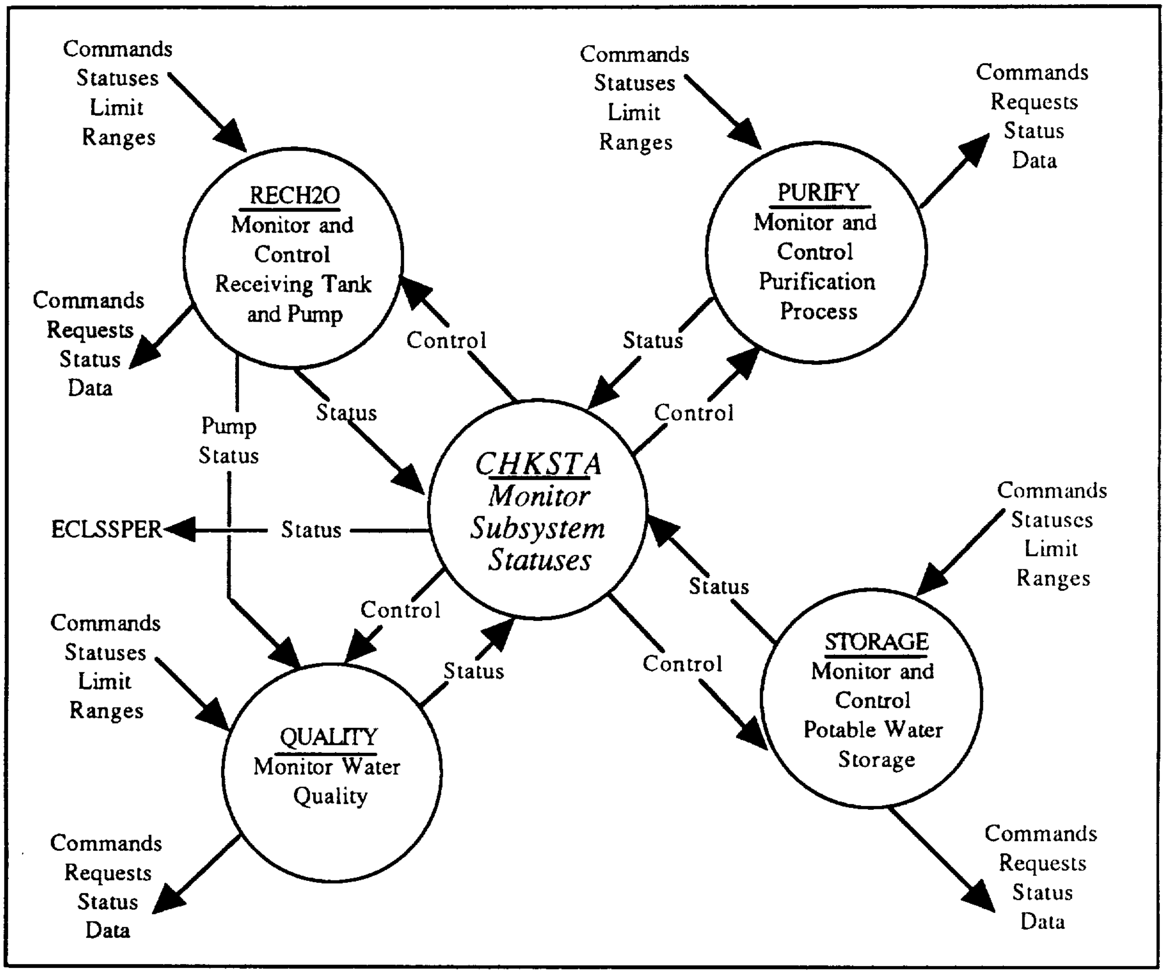


Figure 6. Context Diagram for ECLSS WRM POTH2O Software

As indicated in the context diagram, POTH2O consists of five modules. The central module is CHKSTA. CHKSTA receives status information from each of the other modules and issues controls to each. Further, CHKSTA provides status information to ECLSSPER.

Each of the modules that report to CHKSTA act on the basis of commands from ACTIVATE, limit ranges from WRMLIMITS, and controls from CHKSTA, and each module sends its status to CHKSTA and ECLSSPER, requests to CMD, failure data to ECLSSERR, and display data to DISPLAY. The modules differ in the statuses that are input and the hardware commands that are output. RECH2O receives sensor statuses from the liquid, speed, pressure, pressure transducer,

Short Name	Long Name
CHKSTA	Monitor Subsystem Statuses
RECH2O	Monitor and Control Receiving Tank and Pump
PURIFY	Monitor and Control the Purification Process
STORAGE	Monitor and Control Potable Water Storage
QUALITY	Monitor the Water Quality

and flow meter, as well as statuses from pump and valve, and sends commands to pump and valve as well as passing the pump status to QUALITY. PURIFY receives sensor statuses from pressure, pressure transducer, and temperature, as well as the status from heater, and sends commands to heater. STORAGE receives sensor data from liquid sensor, as well as status from valve, and sends commands to valve. QUALITY receives sensor status from temperature, as well as statuses from pump, valve, and H2OQUAL, and sends commands to valve.

Summary

The ECLSS software is a layered collection of software modules that may be thought of as a logical hierarchy that can be located in physically distinct computers. Although only the path from the ECLSS support software to POTH2O has been traced, analogous tracings could be produced for the other ECLSS subsystems. In this report's discussion of the application of artificial intelligence techniques to ECLSS software, this analogy will be assumed.

3.3 Evaluation of Candidates for Advanced Automation

3.3.1 Introduction

The decisions to implement advanced automation projects using expert systems (ES) techniques are similar to other such decisions, but there are some significant differences. Many of these differences are a result of the way in which ES is perceived and received, and in the nature of the tasks of these software systems. Various schemes have been devised to make decisions on whether or not to implement systems using ES technology. These schemes specify the factors that should be considered in making the decision.

Two important schemes for making the decision to implement an ES have been constructed by Slagel and Wick[23], and the group of Knowledge Based (KB) systems experts enlisted by NASA's Space Station Level I Strategic Plans and Programs Division (hereafter referred to as the "KBS Group") that constructed the Space Station Advanced Automation Study Final Report (SSAA).[9] While there is significant overlap between the two schemes there are also some differences. Each scheme has merit. This section will indicate where specific problems may arise. This section will also make three recommendations concerning the evaluation of the candidate systems in evolving domains, knowledge acquisition, and the types of situations in which various artificial intelligence technologies may be applied.

3.3.2 Comparison of the Schemes

Although both the Slagel and Wick scheme and the SSAA scheme seek to address the same sorts of issues, they differ in the way they construct their appraisals.

The Slagel and Wick scheme provides a computational space in which each consideration influences the final judgment. Thus, a candidate that scores low in a particular area might still be accepted. Given the weights and the function that computes the final candidate value, a final value is generated. There is no hierarchical ranking of considerations accept that which is implicit in the weights and computation function. In this sense none of the characteristics are essential.

The SSAA scheme provides a hierarchy in which essential considerations must score highly before other considerations are appraised. In this sense the general A level criteria would be at the top of the hierarchy and the other criteria would fall lower in the hierarchy. Thus, if a candidate did not do well for the general A level criteria there would be no need to continue the decision process.

There are merits to both approaches. The Slagel and Wick scheme provides a way of creating a global evaluation of a candidate, while the SSAA scheme provides a way for the sponsor of the project to establish demands. Further, it would seem natural for the proposer of the candidate to rely more on the Slagel and Wick scheme that the SSAA scheme. This would be so since by adjusting the weights and computation function the proposer of the candidate could establish the value of the candidate in the terms that he sees to be important. On the other hand, the SSAA scheme would be favored by the sponsor, since it allows the sponsor to clearly indicate what conditions must be satisfied if the sponsor is to support the project.

3.3.3 Recommendations

Both the SSAA scheme and the Slagel and Wick scheme may be used. It is important that in the decision process it be clearly identified which scheme is being used. If this is not done, confusion and poor judgments will follow. In the UAH Research Report Number 824[115], on the demonstration system for the potable water subsystem of ECLSS, the way in which these schemes might be applied and the way in which differences of opinion can be generated was examined. It should be noted that the differences in opinion are reasoned differences. In such a situation it will be important to be clear about what is being claimed, and attempt to identify common grounds.

The following are specific recommenations about these schemes and their use:

The first specific recommendation is that for systems such as the ECLSS, a special set of procedures be established for the candidate systems. As noted in the comments many of the subsystems of ECLSS are currently being developed. This means that any value assigned on the Slagel and Wick model or any judgment made on the SSAA model may change as the subsystem changes. This is extremely important. If the value of ES technology, (and especially rule based systems) is in general accepted as valuable, and if independent judgments are to be made about the value of tools and shells, then the real focus of the schemes will be the domain to which these are to be applied. Unlike many other cases in which the domain and experts about the domain already exist, this is not the case with the ECLSS and many other components of the Space Station. Thus, even if either of the schemes is accepted as the scheme with which candidate evaluations are to be done, modifications must be made and special procedures added to reflect the evolutionary character of the domains and candidates.

The second specific recommendation is that considerations or criteria be added to focus on the problems of knowledge acquisition. It is generally recognized that knowledge acquisition is an extremely difficult task. To some degree the questions articulated by Slagel and Wick address this

difficulty more that the criteria proposed in the SSAA. Without addressing the knowledge acquisition issues, the judgments made about candidates may well be flawed. Consider for example, that at most two of the criteria proposed by SSAA address the knowledge acquisition problems. In terms of an overall judgment, therefore, a candidate may rank very high even though the domain is not sufficiently defined and the experts are both antagonistic and of divergent opinions. This may lead to the failure of the candidate project.

The final recommendation is that more general issues of artificial intelligence (AI) be considered in making evaluations. The schemes seem to focus only on rule based systems. However, what counts as an expert system and the available artificial intelligence technologies are changing rapidly. Thus the following taxonomy is proposed as a guide.

There are several different situations in which AI technology can be added to ECLSS. For a description of ECLSS software, see section 3.2 of this report. As a matter of convenience and uniformity the following classification scheme is proposed:

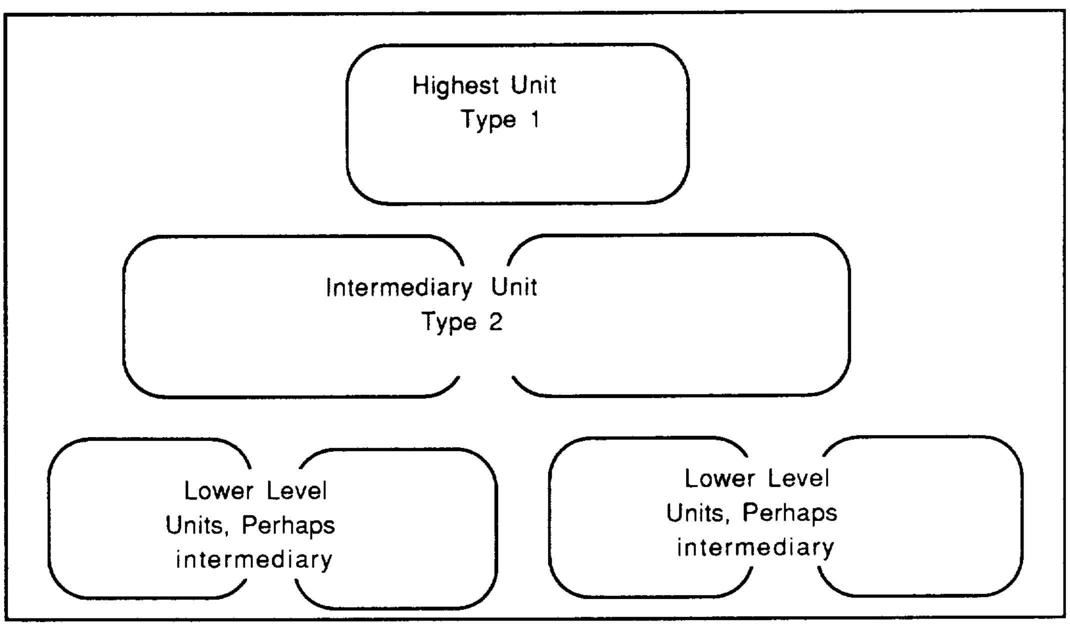
Type	Description	Example
Type 1	Coordination/Diagnosis/ Action for multiple intermediary units	ECLSERR
Type 2	Coordination/Diagnosis/ Action for non-intermediary units	POTH2O
Type 3	Pattern analysis of data	QUALITY

Type 1 situations can be thought of as situations in which a unit processes the data of other units and to which messages are transmitted. Within the ECLSS, ECLSERR would seem to be such a situation. From the point of view of the ECLSS all subsystems report errors to it. Its actions are then directed either to other ECLSS components or to HABOMA. From the point of view of the ECLSS subsystems, ECLSSERR is the highest level unit. All ECLSS subsystems are intermediary. An intermediary system is one which reports to a higher system and itself receives reports from its subsystems. For example WRM and POTH2O are intermediary.

What is special about the Type 1 situation is the domain it engages and the functions it must perform. The domain is not the domain of the hardware in action, but the information generated by intermediary units about the hardware in action. Thus, POTH2O might send up error data to WRM and then to ECLSSERR. ECLSSER could either handle the problem or pass the problem outside of the ECLSS to HABOMA. ECLSERR would ideally need to understand data and messages sent from the intermediaries, and be able to send messages back to the intermediary and to HABOMA.

Thus, what ECLSSERR operates on is information generated by other software units. It may be assumed that the information given to it in this Type 1 situation has been processed, interpreted, and symbolically categorized, and that the ECLSERR must be able to decode it.

The tasks that must be performed in the Type 1 situation are complex and symbolic in nature, heterogeneous in character, and require knowledge about the operation of many systems and how those systems communicate information. These characteristics make Type 1 situations ideal candidates for specifically constructed programs that can perform parsing, string construction, frame analysis, rule application, and other operations for which a LISP processor would seem ideally suited. If this is so, then such situations would call for a hardware scar for the introduction of a LISP processor and software hooks to allow for other units to communicate with it and for it to communicate with other units. Ideally, this would also include specifications for how to add words and units to the LISP based system, a more or less standard syntax for messages, and sufficient administrative support to keep the project at the level of symbolic manipulation of information, data, plans, diagnoses, explanations, etc.



Type 2 situations are those situations in which intermediary units can effectively process information in a rule form. The intermediary units may receive information directly from hardware through a Runtime Object Data Base (RODB) in standard engineering units, from the ECLSS, or from subcomponents. The sorts of diagnostic and supervisory tasks perform by the intermediary units would tend to be specific sorts of tasks ("Determine if the the sensor data is within in range and note what is odd.") These are closely linked to the physical devices that are running under its supervision. In this sense the domain is the process itself. This is an ideal place for a classical rule

base system, although frame based systems may also prove effective.[116] It should be noted that using a CLIPS-like system for these situations would be ideal since, at least potentially, a CLIPS knowledge base could be updated in the same way that an RODB is updated. This would allow modification to the hardware and to the general database (on red-line and-yellow line, for example) to be reflected in the knowledge base.

Type 2 situations call for software hooks to allow communication both up and down from the units. This may not be that difficult since such channels already exist (see context diagrams). However, they might need to be rethought in the light of KBS functionality. Scars do not seem to be an issue here, unless it is in terms of on board memory (RAM) in the unit that will do the processing, or in the size of the mass storage device (disk) that is serving the processor on which the rule based system is running. A far more exotic software hook would be the demand to improve the CLIPS to include genuine backward chaining, frames, metarule, demons, stores, etc. (See UAH Research Report Number 824[115]).

Type 3 situations are the most exotic. These are situations in which the pattern learning and matching capabilities of a neural net could be put to good use. Such situations may be important in the acquisition of sensor data, the capacity to use the patterns of a neural net as a "redundant" sensor, as a store house for the pattern of usage in components, as way of gaining hints about incoming or outgoing telecommunications, etc. The point is that other technologies are up and coming and may also play a significant role. Although neural nets can run on a 80386, and thus are not candidates for scars, a scar may be in order if the neural net software can be thought of as a redundant sensor. In this sense the result of the net would have to go to wherever it is that sensor input goes.

The adoption of the proposed taxonomy would allow a more detailed and disciplined evaluation of candidate projects while also allowing for a greater range of AI techniques to be considered.

3.3.4 Summary

In this section the schemes of candidate system evaluation proposed by Slagel and Wick, and the SSAA have been examined. Each scheme has merit and it is possible to use each scheme if it is made clear which scheme is being used. We have also identified some difficulties in the evaluation of candidates that are dealing with domains and expertise that are in evolution.

In light of this examination we recommend that:

- special procedures be established for the evaluation of candidates that are evolving,
- issues of knowledge acquisition be given a greater role in the evaluation
- a taxonomy be adopted that allows for both the consideration of a wider range of AI technologies and the nature of the different sorts of tasks to which they can be put.

3.3.5 Detailed Description of Each Scheme

3.3.5.1 The Slagel and Wick Scheme

The Slagel and Wick scheme focuses on several categories of questions that must be answered in attempting to generate a reasoned decision to employ ES technology, as summarized in the following table:

Type	Feature	Component
Essential	Users and Management (UM)	Description Weight Value
	Task (T)	Description Weight Value
	Expert (E)	Description Weight Value
Desirable	Users and Management (UM)	Description Weight Value
	Task (T)	Description Weight Value
	Expert (E)	Description Weight Value

The descriptions are simply identifications of features. Ideally these descriptions include some means of operationalizing the feature. The weights and feature values are normalized to generate numbers between 1 and 10. This allows various formulae to be applied in the construction of the overall evaluation of the candidate project.

The particular questions identified by Slagel and Wick are:

Essential Characteristics:

UM1	Do the recipients of the system agree that the payoff is high?
UM2	Do the recipients have realistic expectations?
UM3	Is the management committed to the project?
T1	Is the task natural language easy?
T2	Is the task knowledge intensive?
T3	Is the task heuristic in nature?
T4	Are test cases available?
T5	Can the system undergo incremental growth?
T6	Does the task require little common sense?
T7	Can the task be done without optimal results?
T8	Will the task be performed in the future?
T9	Is the deadline for the system relatively open?
T10	Is the task easy, but not too easy?
E1	Does an expert exist?
E2	Is the expert a genuine expert?
E3	Is the expert committed to the project?
E4	Is the expert cooperative?
E5	Is the expert articulate?
E6	Has the expert been successful at other tasks?
E7	Does the expert use symbolic reasoning?
E8	Can the expert transfer his or her expertise to others?
E9	Does the expert use cognitive skills?
E10	Do multiple experts agree?
E11	Is the expert not being especially creative?

Desirable Characteristics

UM4	Is the management willing to commit time, money, and effort?
UM5	Will the insertion into the work place be smooth?
UM6	Will the system be able to generate explanations?
UM7	Will the system be able to intelligently question the user?
T11	Was the task previously identified as a problem area?
T12	Are solutions explainable and interactive?
T13	Does the task lack real-time demands?
T14	Is the task similar to previous KB efforts?
T15	Is the task performed at many locations?
T16	Is the task performed in a hostile environment?
T17	Does the task involve subjective factors?
E12	Is the expert unavailable when the system is needed?
E13	Can the expert become intellectually attached to the project?
E14	Does the expert feel comfortable with the project?
E15	Is the expertise loosely organized?

These questions set out a basic structure for determining whether a knowledge based (KB) approach is appropriate. As noted earlier various rating functions could be applied to the values generated in response to these questions. Within the Slagel and Wick scheme it is important to notice that none of the questions have an essential character. Any of the questions could be set to a low or high value without directly affecting the decision to employ an KB technology. An alternative is to set out criteria that demand to some degree that characteristics be satisfied. This alternative would establish a set of questions to which it is essential to have high values if the candidate is to be accepted. This is the approach taken in the Space Station Advanced Automation (SSAA) final report. Rather than indicating questions and a ranking function, the report sets out criteria for KB projects.

3.3.5.2 The SSAA Scheme

The SSAA Final Report[9] established various evaluation criteria for the evaluation of advanced automation projects. These can be separated in to General, Baseline and Evolution criteria. The three kinds of criteria indirectly correspond to the types of Slagel and Wick. However, the SSAA scheme does not provide for a general computation. It specifies certain essential characteristics that a candidate project must satisfy, if the candidate is to be accepted. Further the KBS Group indicated three levels of importance ranked A,B and C. The levels indirectly correspond to the attribute values of Slagel and Wick. However, it should be remembered that these levels of importance seem to be constructed so that if a candidate does not score well at the A level, its scores at the B and C level do not matter. In this sense the SSAA criteria forms a hierarchy.

The SSAA report was generally positive in its appraisal of the potential for ES applications to ECLSS: "(particularly water and air regeneration) -- major advantages for a KB approach were lack of crew experience with new Space Station technology and relative technical simplicity of the underlying systems. Major disadvantages were the life-criticality of such a system and lacking internal experience or champions (advocates) within NASA."[9]

General Criteria - Level A

These criteria stand at the top of a pyramid of criteria. They are both the most general criteria and the most necessary to be satisfied. In this sense they can be understood as necessary conditions for a successful project. It should be understood that even for a potentially successful project not all of the criteria need to be satisfied, nor must they all be satisfied to the same degree. Thus, it is the massed action of these criteria that need to be satisfied.

- Presence of a strong user champion

  Comment - A user champion is an advocate who is personally involved and is within the sponsoring agency. The SSAA final report indicates that the astronauts would be in favor of such a system. This is important. However, since any advanced automation for ECLSS would include as users the space life sciences group and system design engineers, these groups should also be interviewed. The interviews should focus on both the perceived need for such systems and the kinds of features desired.

- Presence of a strong management/executive funding champion

    Comment - The executive champion is an advocate committed to ensuring that the development process is protected and resources are made available, even in difficult times. Although the report indicated that ECLSS is a good candidate it is not yet clear who the project champion will be.

- Strong feeling of participation by all user groups including crew

    Comment - This can only be achieved if the astronauts and others are interviewed and kept informed. It would be desirable to have some mechanism by which the end users can feed their recommendations to the team that designs and builds the system, therefore allowing for maximum perfomance and satisfaction.

- Existing expertise and agreement on heuristic solution

    Comment — As the SSAA report noted much of the ECLSS system is currently being developed. This means that it will be difficult to identify experts. In this sense the evaluation of candidate systems for ECLSS will either receive a low rating, or will receive special attention. The reason for this is that in most candidate evaluations both the system and the expertise exits. This is not the case for the ECLSS. Thus, a procedure in which both the development of the ECLSS system or subsystem and the ES applications are appraised during the evolution of the whole system would seem to be needed.

- Functionality cannot be achieved cost effectively without a knowledge based system

    Comment - The SSAA report provides an illustration of the intent of this criterion. For example, 'PI-in-a-box', a three man-year effort on a MacII in Nexpert, would be about $250,000. The report indicates that this should be a typical case. On the other hand the trend analysis expert running on 5 Sun4 class machines and an optical Local Area Network (LAN) under the efforts of a senior computer engineer, senior programmer, and 4 junior programmers comes out at $1,000,000 for three years in a 10 man-year effort. In short there seems to be a large range in what would count as being cost effective. The determination of the satisfaction of this criterion should rest on an economic analysis.

- Ability to both qualitatively and quantitatively evaluate the success of the application

    Comment - This would be specific to each instance of the KB. The need is for clear criteria of what the system is to do and how it is to do it at the outset. Anecdotal evidence is not sufficient according to the report. In the case of ES systems that are evolving with the

physical system and expertise about it, special procedures for evaluating the satisfaction of this criterion may be needed.

- Ability to demonstrate incremental progress

  Comment - This criteria seems to represent general managerial practice, however in the use of KB technology there are some difficulties. The ability to demonstrate incremental progress hinges on what is to count as a demonstration. An improvement in the organization of the system might make a system run faster while a sudden increase in knowledge content might make it run slower. In order to satisfy this criterion some clear account of what counts as a demonstration and what counts as incremental progress must be established.

- Potential horizontal generality of application

  Comment - This criterion contains several different issues. On the one hand the generic parts of a KB system can be extended horizontally. However, it is very unlikely that the most domain specific claims will be able to be extended. In order to satisfy this requirement some notion of abstraction is needed, and that will require software tools for support. For example, a larger frame based reasoning system may be able to be extended and allow some of the knowledge in the frames can be used horizontally. Such systems may prove to be rare and may require new software techniques to be developed. In short, this criterion should be made more specific in terms of its intent.

- Availability of test cases

  Comment - Clearly it is important to have test cases available and to use them in testing the produced system. However, it should be noticed that too great an emphasis on test cases may lead to undesirable results in terms of influencing the methodology of the knowledge acquisition, and the type of reasoning system to be employed. Case based reasoning may be good even if it does not perform as well as another approach on the test cases. It should be noticed that the condition of quantitative and qualitative evaluation can produce answers that are at odds with test case results. This possible conflict upon the satisfaction of criteria should be taken into account in any appraisal.

- Ability to firewall the application from doing harm

  Comment - This seems to be a much more technical criterion that the others in this group. To firewall the system entails some way in which the system can be turned off. That seems to be a design decision that is commensurate with, if not equivalent to, the demand for a

person to be in the control of the system. If this is the intent, then the demand can be satisfied. If on the other hand, the intent is that any such system must also be able to diagnosis what it itself is doing, then this becomes a hard problem. It would require the system to both reason about other systems and itself. Such systems would be difficult to construct would require the cooperation of other software components, and use an increased amount of computing resources.

• Bounded technical complexity

Comment - It is an accepted principle that KB systems should operate on problems that are neither too hard nor too easy. The difficulty with the application of this criterion to the ECLSS is that since the ECLSS is under development the appraisal of the the technical complexity may change as the system changes. This again indicates the need for some sort of co-evolutionary appraisal procedure.

General Criteria - Level B

Again these are general criteria to be applied to a project. Their importance is lower than the Level A criteria. However, these criteria do raise important issues.

• High visibility

Comment — This criterion seems to reflect the political and social dimensions of the advancing KB technology, and would not be a criterion for a traditional software program. The attempt to satisfy this criterion could lead to compromises in the A level criteria. However, since the criteria are hierarchical, no level of visibility, or lack there of, should alter the decision at the A level.

• Model based reasoning approach that allows for multiple uses

Comment - The suggestion seems to be that while rules are a good knowledge representation for many problems, they are neither the only representation, nor the best for specific problems. One should also look forward to new techniques, in particular model based reasoning. In this sense, CLIPS may very well be an undesirable tool. The development of other kinds of systems will depend upon the inclusion of tools in the Software Support Environment (SSE).

• Automate what people like to do least; the routine; the day-to-day

Comment - Bureaucratic agents can be of great service. Routine reports and monitoring should be automated. This suggests other sorts of application for advanced automation. It should be noted, however, that some of these tasks may be either so computational or so routine that AI techniques are not required.

• Capitalize on what has been started.

Comment — As with several of the other proposed criteria, this criterion seems to be either a directive as to the types of projects that ought to be proposed, or a general management practice claim. If it is the former it may be unduly restrictive, and if the latter unnecessary.

• Start with advisory mode and evolve if appropriate to a close-loop system.

Comment — This seems to be a directive about how to plan the development of a candidate, and an injunction against starting with a closed loop system. This might better be thought of as a specification rather than a criterion.

• For space based applications the system should be one that can be put into operation on the ground first.

Comment — This proposed criterion again appears to be a directive, rather than a criterion for appraisal. It is also unclear why a well tested system should be put into operation on the ground first. If the testing which can take place on the ground, has been done this would seem to be sufficient to place the software into an advisory mode on board. Further, putting diagnostic software into operation on the ground first seems to be a testing procedure, since many of the faults may well have been detected and recovered from on board.

• Use design knowledge.

Comment - For the ECLSS there would be a very strong possibility of satisfying this criterion if the co-evolutionary strategy is adopted. There are two significant alternatives to the capture of such design knowledge. The first is to embed the capture of this knowledge within the design of the software system. This may not prove to be an ideal way to proceed, since the Knowledge Engineer (KE) would be focused on the acquisition of the knowledge related to the projects goal. On the other hand it would allow the KE to have a greater understanding and contact with the experts. The second alternative is to establish a separate project for design knowledge capture and for the production of advanced automation for design. This would have the benefit of being a focused effort that could

produce both knowledge and tools that could be used horizontally, but would increase the expense of the project since another team would be needed, and may increase interpersonal conflict since the experts may overlap and be the focus of two distinct KE groups.

General Criteria - Level C

The third level of General Criteria is designed to place the proposed system in the context of other projects.

- The system can be evolved to higher functionality after deployment.

  Comment — This seems to be a specification of the B level stipulation that systems start in the advisory mode.

- The system can use non-ES techniques.

  Comment — It would seem that an ES system if it is to evolve at all must make use of non-ES technologies, particularly data bases, networks, and communication systems. If this is the intent of the criterion, it is reasonable enough. However, it might also mean that there should be a non-ES backup system. This would pose problems. If the non-ES is a good enough backup system, then there is no need for the ES unless a specific advantage (speed, efficiency) can be shown. Further, the construction of the backup will add to the cost of the project.

Baseline Criteria - Level A

The second variety of criteria specified in the SSAA concern the baseline of the system. These seem to be intended to capture the conditions that the system must satisfy in order to be included in the Space Station Freedom.

The Level A criteria and the Level B criteria seem to be greater specification of related general criteria.

- Medium to high payoff

  Comment — In order to be clear about this criterion some way of computing payoff is needed.

• Low technical risk

Comment — Given that the project has a bounded technical complexity, this criterion would seem to refer to the calculation of the risk. Some formula should be specified to compute the risk, and some scale should be established.

• Reduction of crew time spent in routine and maintenance functions.

Comment - There was a positive attitude of crew towards the use of KB systems on the Space Station Freedom. They expressed a very strong desire to spend as much time as possible on the Space Station carrying out scientific experiments and as little time as possible worrying about maintenance and other housekeeping chores.[9] As the SSAA report noted, the ECLSS would seem to be a good candidate for this reason.

• Expected high user acceptance

Comment — Interviews with users about the candidate, and involvement of the users in the design are important factors in satisfying this criterion.

• Effective ground evaluation prior to deployment

Comment - In the case of the systems that might be used for ECLSS, this could be satisfied by having a tight coupling of the knowledge engineer with the systems engineers. This would allow the full ECLSS system and the advanced automation projects to co-evolve. If this strategy is acceptable the software system would undergo continual testing along with the ECLSS hardware on the Core Module Integration Facility (CMIF).

Baseline Criteria -Level B

• Can be tested on Shuttle

Comment — This will be very difficult in terms of the technology of ECLSS for Space Station. On the other hand it might be of value to design a separate system for the Shuttle that tests the ideas in the system. This would, of course, add time and money, to the development of the candidate.

• Actively supports other software/hardware units

Comment - For the ECLSS systems examined in this report the most important software support would come from the "Runtime Object Database" software for the Space Station. As this software becomes available it would be necessary to tie into it, since it appears that

all sensor reading will be sent to the distributed database systems. In similar ways the full ECLSS system would need to tie into the display system and the communications system. In the early use of the system these factors would not be as significant since the system may be stationed on the ground until its "track record" is demonstrated.

Evolution Criteria - Level A

The evolutionary criteria focuses on the possible path from a ground based assistant to an embedded system in the Space Station. These criteria in large measure repeat criteria already encountered.

• Low to medium technical difficulty

Comment — As above, a scale is needed.

• High payoff

Comment — As above, a formula is needed.

• High user demand

Comment — This will depend on the reaction of users to the initial system, and suggests a continuing role for users in the development and evolution of the system.

• Strong attention to integration of multiple systems

Comment — Assuming that the attention to non-ES systems has already been determined, this criterion seems to focus on the coordination of multiple intelligent systems. This is important as the technology is used at various levels. In some sense this should be a general criterion rather than an evolutionary criterion since for some of the ECLSS candidates it will be important for them to cooperate in some fashion.

3.4 Recommendations For Candidate Sites For Advanced Automation

As indicated earlier in this report there are two ways in which candidates can be appraised. From the proposer's point of view the Slagel and Wick scheme seems appropriate, while from the sponsor's point of view the criterial scheme of the SSAAReport seems appropriate. In either case, however, we will not be able to conduct a complete appraisal of the candidate sites that we will propose. We will focus on those issues most closely related to the technological and task aspects of the candidate proposal and appraisal process. To this end, the section will be divided into several subsections. The first section will address the issue of isolating the relevant criteria, the second will examine potential candidate sites within the general framework of the previous parts of this report that focused on the path to CHKSTA in the POTH2O unit of WRM, and the final section will present our reasoned recommendations.

3.4.1 Criteria

In the Slagel and Wick scheme, there are three sorts of questions. Questions about users and management are clearly beyond the scope of this report. To address these questions, the potential managers and users must be interviewed, and this is not possible given the scope of the task. A second group of questions concerns the experts themselves. This would require the identifying and interviewing the experts, and, again, this is beyond the scope of this project. Although we recognize the importance of these groups of questions there is reason to claim that there is a primacy to the questions concerning the task. The questions in this group will be the focus of our analyses and recommendations.

As noted earlier, the SSAA scheme adopts the point of view of the sponsor of the system and uses a criterial approach. Although the scheme uses a division into general, baseline, and evolutionary criteria subdivided into A, B and C levels, it is possible to interpret the criteria in terms of their user and management, expert, and task components. We will focus on the general criteria that most clearly correspond to the intent of the task grouping of Slagel and Wick.

The issues, phrased as questions, can be grouped into three categories. Task specific issues are those issues that are directed to the domain that is to be automated. These issues are subdivided into supporting and rebutting factors. The supporting factors are those that favor the use of an automated knowledge technology, while the rebutting factors provide reasons for not adopting such technology. The evaluation issues are directed to the ways in which the advanced automation product can be appraised. The implementation issues are directed to those factors that the product must address when implemented.

The fourteen items, listed below, provide a list of considerations that is both extensive enough to address a variety of core concerns and compact enough to be readily applied. Implicit in this group of items is the primacy of the task. This primacy is reasonable since the other two groupings are dependent upon it. If the task is not a reasonable candidate in terms of these considerations, then even if the concerns of managers, users, and experts are supportive of the candidate project, it would not be successful since it is not the kind of task that could be successfully automated with either today's resources or the resources that might be expected in the near future. This is not to say that the projects that would be more reflective of the concerns of managers, users, and experts ought not to be attempted. Many of them should. However, these projects would require more extended research, and would not be directly applicable to the context of the ECLSS within Space Station Freedom.

Type	Item	Question	Reference
Task specific Supporting factors	1	Is the task knowledge intensive? Can design knowledge be captured and used?	S&W T2; SSAA General level B
	2	Is the task heuristic in nature? Can a model based reasoning approach be used?	S&W T3; SSAA General level B
	3	Does the task involve subjective factors?	S&W T17
	4	Is the task easy, but not too easy? Does the task exhibit bounded technical complexity?	S&W T10; SSAA General level A
	5	Was the task previously identified as a problem area? Would the software automate what people like to do least; the routine; the day-to-day?	S&W T11; SSAA General level A
Task specific Rebutting factors	6	Is the task natural language easy?	S&W T1
	7	Does the task require little common sense?	S&W T6
	8	Can the task be done without optimal results?	S&W T7
Evaluation issues	9	Are test cases available? Can the success of the application be evaluated qualitatively and quantitatively?	S&W T4; SSAA General level A
	10	Can the system undergo incremental growth?	S&W T5; SSAA General level A
	11	Is the task similar to previous KB efforts?	S&W T14
	12	Is the task performed at many locations? Is there a potential horizontal generality for the application?	S&W T15; SSAA General level A
Implementation issues	13	Are solutions explainable and interactive?	S&W T12
	14	Does the task lack real-time demands? Can the application be firewalled to prevent harm?	S&W T13; SSAA General level A

3.4.2 Potential sites

In the previous discussions of the criteria for the appraisal of candidates, three types of candidates were examined.

Type	Description	Example
Type 1	Coordination / Diagnosis / Action for multiple intermediary units	ECLSERR
Type 2	Coordination / Diagnosis / Action for non-intermediary units	POTH2O
Type 3	Pattern analysis of data	QUALITY

These three types will furnish a point of departure for considering candidate systems.

Type 1 candidates are distinguished by their communication and integration functions. A Type 1 candidate absorbs information and knowledge that has to some degree already been processed by a lower level system. The obvious sites for this type of automation are at the level of the ECLSS support software (ECLSSMGR). However, not all of the components are equally good sites.

ACTIVATE, although a central element of the the ECLSS support software, would not appear to be good site. The most direct reason is that the function of ACTIVATE does not seem to be one that is amenable to heuristic reasoning. Rather ACTIVATE would seem to function as a bureaucratic communications agent. It activates different subcomponents, but does not itself make decisions on what should or should not be activated. This seems apparent since both CMD and INHIBIT perform operations that would require the decision making (verification, validation and inhibition). Further in the crucial area of Fault Detection, Isolation and Recovery (FDIR), it is the ECLSSERR subcomponent that both receives failure data and reports critical errors to HABOMA.

In its present form, ECLSSPER would also not appear to be a good site for artificial intelligence based advanced automation. While a good case might be made for the use of such techniques in the analysis and interpretation of performance and trend data, the function of this unit would seem to be the mathematical analysis of status data and the reporting of short-term trend data to HABOMA. In this sense ECLSSPER acts as a computational engine, and not heuristic or knowledge intensive engine. Further, the operation of ECLSSPER should be such that subjective factors are not relevant but real-time operation is. Both of these count against this site. However, should the responsibilities of ECLSSPER be expanded to encompass a more active role in the managing of performances, areas for application would be created.

The INHIBIT and CMD modules are closely linked. While the tasks that these systems perform might be knowledge intensive and might require heuristic reasoning, it is not transparently clear that this is so. It might be the case the functions of these units are essentially database and interpreter functions. INHIBIT, if so requested, consults the database of inhibited functions and sends its results on to CMD. CMD might check to see that the requests and commands coming into ECLSS are consistent and syntactically correct. In this sense, CMD acts as an interpreter and not as a knowledge intensive decision aid. Alternatively, the two units might act on rules or on past cases to make decisions about what functions should be inhibited and which should be allowed. Currently, there is not sufficient information to decide which of these options is more likely to be the case. Thus, until there is more specific information on these components, they would not appear to be good candidates since their functionality might be accomplished with more traditional techniques.

Of the remaining sites one, ECLSSERR, is a classical application of AI advanced automation, and the other, DISPLAY, is somewhat novel. The Fault Detection Isolation and Recovery (FDIR) tasks of ECLSSERR are essential a combination of a diagnosis task and a configuration task. Each of these is a task at which knowledge based systems have proven successful in the past. They are knowledge intensive, heuristic, and bounded. They express the subjectivity of experts and are not natural language intensive. Although the development of such a system might prove to be complex and require a variety of strategies to be used, an advanced automation system might prove valuable. Further, given the fact that such systems can be tested against test cases based on data acquired during the design and testing phases of both hardware and software development, ECLSSERR would seem to be an ideal candidate. DISPLAY, although not as clearly an ideal candidate, would also seem to be a good candidate, if it is noted that the data that is to be displayed to the user can be enhanced by applying knowledge about human computer interaction and heuristics about the relation of data to be displayed. While the overall interaction of the display system with the user may create natural language problems, the actual display of the data ought not. On this basis the DISPLAY component of the ECLSS software support system would also seem to be a good candidate.

Thus, at the level of the ECLSS software support, the two best candidates are ECLSSERR and DISPLAY.

Dropping to a lower level in the ECLSS, the WRM software presents a more expanded selection of candidates. In part, this is due to the fact that types of subsystems present inside of the WRM are Type 2 systems. Since the domains of the WRM subsystems are more clearly defined, they have been the primary targets of knowledge based systems. For example, both POTH2O and HYGH2O manage the operations of the relevant software on the basis of data, commands, and quality statuses. In a way analogous to that of the ECLSSERR, the tasks which each of these units

perform are a combination of diagnosis and configuration. The diagnosis comes in terms of the subparts of the system with information about failures being sent to the ECLSERR for further analysis. The configuration aspect is represented in terms of the configuration of information rather than hardware and software. That is, inside of each subcomponent is a bureaucratic unit that attempts to build and send messages to other ECLSS units. Although this bureaucratic unit is not as knowledge intensive or heuristic as the unit that identifies failures, it may have some knowledge intensive aspects in initiating its requests. However, even if the configuration aspect is minimal, the diagnostic aspects of these two units are rather strong and recommend themselves as candidate systems.

The H2OQUAL unit is somewhat different. The function of this unit is to make a judgement about the quality of the water for both the hygiene and potable systems on the basis of data concerning iodine, conductivity, pH, and TOC. In a certain sense, the functions of this unit are separated from those of POTH2O and HYGH2O in terms of the physical and chemical aspects of the systems. This will become more apparent in the discussion of the components of POTH2O (below). However, the task that H2OQUAL performs is essentially diagnostic. It attempts to determine the quality of the water. This operation would seem to be both knowledge intensive and heuristic. Knowledge about the chemical processes and the limits of acceptability would be required to decide whether the quality of the water was satisfactory. This might also require that tradeoffs and sacrifices be made at various times, knowing the condition of the system and the need for water. It is reasonable to think that there would be functions of URINE that would be similar to the functions of the foregoing units. The documentation gave no evidence that this has been carefully examined at the present time.

Thus, at the level of WRM the best candidates are POTH2O, HYGH2O, and H2OQUAL.

One level deeper in the ECLSS are subcomponents of POTH2O. At this level CHKSTA controls the physical operation of the various components of the potable water system. The control at this level seems to be neither knowledge intensive nor heuristic. Rather CHKSTA can be understood as responding to statuses in set ways by turning equipment on and off. The RECH2O, PURIFY, STORAGE, and QUALITY units are the ones that make the determination of the successful or unsuccessful operation of the physical equipment and send failure data to ECLSSERR. While the monitoring of such data can be understood as knowledge intensive process, it might also be though of as a pattern recognition problem, a Type 3 application. As such these sites might make ideal candidates for beginning to apply neural net techniques. These techniques are not directly addressed in terms of the items for evaluating candidate systems. However, as the technology of neural nets begins to stabilize it might be possible to include them at these locations. Currently, a rule based system could be applied, but might prove too brittle to contend with sensor input at this level. Further, it should be noticed that the kinds of tasks that

these components of POTH2O perform, are physical in nature. In this sense they may prove to be less knowledge intensive than the chemical monitoring by H2OQUAL, since they would be less susceptible to the vagaries associated with the absorption and removal of various chemicals. Since the physical abilities of the units at this level can be well established, and since the tasks are essentially repetitive, it might be possible to train and test a neural net on board the Space Station itself. Finally, the training of the neural nets, might be used as an opportunity for knowledge acquisition. This is an important issue if recent work on the conversion of neural net states to rules proves effective.[117]

Thus, while the units of POTH2O might profit from the use of knowledge based software, they might profit more from a neural net approach.

3.4.3 Recommendations

3.4.3.1 Type 1 Applications - ECLSSERR

Item	Question	Response
1	Is the task knowledge intensive? Can design knowledge be captured and used?	The ECLSSERR is a clear case for the application of diagnostic reasoning that uses knowledge to make judgments. Since the knowledge used would include design knowledge a project at this site would be supportive of the desire to capture design knowledge.
2	Is the task heuristic in nature? Can a model based reasoning approach be used?	As in any diagnostic task, the use of heuristics is pronounced. A model or cased base approach could be used, in the attempt to find the case with the best fit. This would also encourage the development of new tools.
3	Does the task involve subjective factors?	Although subjective may be a misleading term, this task does involve the use of expert judgement.
4	Is the task easy, but not too easy? Does the task exhibit bounded technical complexity?	The task is bounded yet sufficiently complex to warrant automation.
5	Was the task previously identified as a problem area? Would the software automate what people like to do least; the routine; the day-to-day?	FDIR is always a problem area. The use of check sheets or manual diagnostic aids a prone to human error. Many cases of apparent error could be weeded out by a knowledge based system and recovery automated for routine operation.
6	Is the task natural language easy?	Natural language input is not required.
7	Does the task require little common sense?	Common sense is not an issue.
8	Can the task be done without optimal results?	The diagnosis can err on the safe side and be satisficing rather than optimal.
9	Are test cases available? Can the success of the application be evaluated qualitatively and quantitatively?	Test cases can be generated as the hardware is developed. The qualitative appraisal of the system would depend on both the DISPLAY and user satisfaction
10	Can the system undergo incremental growth?	This may prove difficult. However, some classes of problems might be attacked before others.
11	Is the task similar to previous KB efforts?	Yes, there are many diagnostic style systems.
12	Is the task performed at many locations? Is there a potential horizontal generality for the application?	This is not likely unless other space vehicles or stations are built with similar hardware and the domain knowledge is very similar. However, see below for additional information.
13	Are solutions explainable and interactive?	Explanations would be desirable and they can be built. The operation of the system need not be interactive.
14	Does the task lack real-time demands? Can the application be firewalled to prevent harm?	Some of the operations of the system are not real time. The operations that demand real-time action should be trapped before being passed to ECLSSERR. It would seem reasonable that a toggle could be incorporated to turn the system off, and also allow a human to have the final judgement.

Comment — ECLSSERR is in many ways an ideal candidate for ES technology. Using an ES at this level may centralize many of the diagnostic functions at lower levels and thus remove some redundancy from the overall software. Alternatively, redundant lower functions can be kept to add an added margin of safety. The kind of task that ECLSSERR performs is one in which ES technology has had success. It should be noted that for this application of knowledge based systems to be successful, it might well be necessary to build better tools that would support the ES paradigm and the use of a blackboard structure. Some sort of generic blackboard through which results, and perhaps tasks, could be shared should be investigated.

3.4.3.2 Type 1 Applications - DISPLAY

Item	Question	Response
1	Is the task knowledge intensive? Can design knowledge be captured and used?	Although not knowledge intensive in the classical sense, a good case can be made that the presentations in display ought to reflect knowledge about cognition and computer-human interaction.
2	Is the task heuristic in nature? Can a model based reasoning approach be used?	Since the unit must deal with a wide variety of information heuristics about which information to display when should be incorporated. A user model that differs from user to user should prove to be very effective.
3	Does the task involve subjective factors?	The user model should reflective individual cognitive styles.
4	Is the task easy, but not too easy? Does the task exhibit bounded technical complexity?	The design of what is to be displayed is of bounded complexity.
5	Was the task previously identified as a problem area? Would the software automate what people like to do least; the routine; the day-to-day?	Traditionally, displays and interfaces are problems for any system
6	Is the task natural language easy?	This would depend on the design
7	Does the task require little common sense?	To the degree that it does this would have to be built in.
8	Can the task be done without optimal results?	Yes, as long as the most important information is clearly and promptly displayed.
9	Are test cases available? Can the success of the application be evaluated qualitatively and quantitatively?	It would be difficult to generate test cases, but the users of the system should be able to supply clear qualitative evaluations.
10	Can the system undergo incremental growth?	This would seem to be possible.
11	Is the task similar to previous KB efforts?	Many knowledge based system have had to contend with this domain, and good interfaces have been developed.
12	Is the task performed at many locations? Is there a potential horizontal generality for the application?	This would depend on the number of displays on the Space Station and the incorporation of the presentation technology in other efforts.
13	Are solutions explainable and interactive?	While there may be little need to explain the operations of the unit, there may be a great need to make it very easily interactive.
14	Does the task lack real-time demands? Can the application be firewalled to prevent harm?	Speed is important to any display. There is little need to firewall the application since it does not control any processes.

Comment — DISPLAY offers many opportunities for the application of AI techniques. Although these are to be considered to be some what novel as compared to the well established ES technologies, they represent important sites for advanced automation. Ideally the display, through a user model should adjust itself to the user. Different crew members would have different user models that would allow the display to construct appropriate text and explanations in a way informative to that crew member. This is important if the crew members are reasonably anticipated to have different levels of experience with the ECLSS. Further, the display should allow for both hypertext links which would allow the user to follow information in his or her own way, and prescribed links that would coerce the user to viewing all of the important information available through display. The final element which would be valuable to add to DISPLAY would be an intelligent word processor that would precompose any reports that the user may need to construct. These precomposed reports could be edited and sent along the way without the user having to expend a great deal of effort in a routine operation.

3.4.3.3 Type 2 Applications

WRM: POTH2O, H2OQUAL, HYGH2O

Item	Question	Response
1	Is the task knowledge intensive? Can design knowledge be captured and used?	Each of the tasks within WRM would seem to have a knowledge intensive component, and design knowledge might be an important part of the knowledge that the system needs.
2	Is the task heuristic in nature? Can a model based reasoning approach be used?	The diagnostic nature of the tasks are heuristic, and case and model based reasoning can be applied.
3	Does the task involve subjective factors?	Only in the sense of expert judgement.
4	Is the task easy, but not too easy? Does the task exhibit bounded technical complexity?	While the tasks are complex, they are technically well defined.
5	Was the task previously identified as a problem area? Would the software automate what people like to do least; the routine; the day-to-day?	Problems with the new hardware are bound to arise and many of the problems when diagnosed might have clear solutions. It would be better to use advanced techniques than to overload the memory and talent of the crew.
6	Is the task natural language easy?	Natural language is not a factor.
7	Does the task require little common sense?	Common sense does not appear to be an issue.
8	Can the task be done without optimal results?	As in the case of ECLSSERR, satisficing is acceptable.
9	Are test cases available? Can the success of the application be evaluated qualitatively and quantitatively?	Test cases can be generated as the hardware is developed. The success of the system might be measured in terms of the number of problems it solves without human interaction.
10	Can the system undergo incremental growth?	Yes, new diagnostic units can be added, and old one's improved.
11	Is the task similar to previous KB efforts?	Yes.
12	Is the task performed at many locations? Is there a potential horizontal generality for the application?	The same basic techniques can be applied in many of the ECLSS subsystem and perhaps in other systems. Since all knowledge based systems are domain dependent, the systems themselves cannot be transferred. However, the case POTH2O) and HYGH2O may be atypical, and these might be unified.
13	Are solutions explainable and interactive?	Explanations can and should be generated when needed.
14	Does the task lack real-time demands? Can the application be firewalled to prevent harm?	Many of the tasks in the WRM are either not real-time or real-time is sufficiently long that no problems are created. The system can be firewalled in the manner of ECLSSERR.

Comment — The units of the WRM are the sort of units on which much of the ES effort of the past few years has been expended. In this sense they are ideal candidates. However, it should be noticed that in each case careful coordination with ECLSSERR must be established. Whether, the diagnostics at the lower level are to be used as filters or checks is important. It should be noted that the redundancy provided by having diagnostic ES systems at two different levels may provide for an increase in firewall protection, but will also add to the complexity of the systems. At this level and using only ES technology much can be done, and it is reasonable to think that there are many similar situations within the total ECLSS. However, it should also be noted that these applications are highly domain specific. As such it is unlikely that they will exhibit any horizontal generality, and to the degree that they do this may argue for a software unification as in the case of H2OQUAL. Again the tools for implementing an ES at these sites might profit from the availability of improved software or hardware that would readily support opportunistic inferencing and the object oriented paradigm.

3.4.3.4 Type 3 Applications

POTH2O: RECH2O, PURIFY, STORAGE, QUALITY

Item	Question	Response
1	Is the task knowledge intensive? Can design knowledge be captured and used?	Although the tasks could be considered to be knowledge intensive. It might be better to consider them to be pattern intensive.
2	Is the task heuristic in nature? Can a model based reasoning approach be used?	The task is heuristic to the degree that rules of thumb can be used to recognize patterns.
3	Does the task involve subjective factors?	Not in essential ways.
4	Is the task easy, but not too easy? Does the task exhibit bounded technical complexity?	The task can be done with knowledge based systems, but newer technologies might prove to be better.
5	Was the task previously identified as a problem area? Would the software automate what people like to do least; the routine; the day-to-day?	Sensor problems are difficult. There is always a desire to add another sensor. It might be possible to use either a knowledge based system, and knowledge based system with a simulation, or a neural net to provide the needed data and checks on the data.
6	Is the task natural language easy?	Natural language is not relevant.
7	Does the task require little common sense?	Common sense is not an issue.
8	Can the task be done without optimal results?	There is a greater demand on optimality for these units. However, when gauges become faulty or fail to operate advanced systems may provide a partial remedy.
9	Are test cases available? Can the success of the application be evaluated qualitatively and quantitatively?	Test cases could be developed, and for neural nets these could be provided as training cases.
10	Can the system undergo incremental growth?	As new patterns are discovered they could either be explicitly added as rules or implicitly added as training instances of a neural net.
11	Is the task similar to previous KB efforts?	Expert systems have been added to sensors and programmable controllers. However, this is still a rather new area, especially the neural net technology.
12	Is the task performed at many locations? Is there a potential horizontal generality for the application?	There is great potential in the development of a system that allows for a fall back position when sensors malfunction. If such systems proved their worth they could exhibit horizontal generality.
13	Are solutions explainable and interactive?	While interaction is not a problem the explainability of the results of the system might be. The explanation of pattern recognition is difficult.
14	Does the task lack real-time demands? Can the application be firewalled to prevent harm?	Real time is needed in many of these cases. If there are not too many rules, or if the neural net is fast enough this would not be a problem. It would be difficult, but not impossible, to firewall a system at this low level.

Comment — The application of ES technology at this level may prove useful. However, this level would also seem to be an ideal site for using neural net technologies. Recent advances in this software technique have generated optimism that not only will neural nets prove to be good pattern recognition tools, but also that they may prove to be good sensor analyzers or even emergency sensor replacements. The latter is the case when some sort of voting procedure is used on sensor groups. The failure of any given sensor may lead to it being replaced by a neural net. It should also be noted that neural nets may prove to be good knowledge acquisition tools at this level, and, therefore, improve upon some aspects of the performance of more traditional ES systems by improving the knowledge that they use in inferencing.

We would recommend that the process of constructing ES systems begin with the Type 2 cases inside of WRM. These sites are well suited to the use of ES technology and are the most familiar to knowledge engineers and those who construct ES systems.

The next site to be attacked should be DISPLAY. The interaction of the user with the system and the need for explanations would strongly support the application of advanced techniques in this area. This will be of great importance if the ESs at the WRM level are initially placed in an advisory mode. A system that was only able to display data as advice might impose a cognitive burden on the user in those cases in which the user was either unsure of the advice or believed that a better course of action was possible. Thus, we believe that the DISPLAY unit will be intimately connected to the perceived quality success of any ES.

A third step in the implementation of advanced automation techniques would be to apply them to ECLSSERR. This presents several challenges even though the basic functions which the ES would perform have been successfully demonstrated in other systems. The most obvious challenge is that of coordinating not only the units that lead to the potable water system, but all of the other units as well. As an manager the ECLSSERR must be able to focus its attention on those parts of the ECLSS system that most need attention. In some cases this may be AR, in others WRM. Further, it should be clear that some of the units of ECLSS may require careful coordination. This would be the case in the relation of THC to WRM, for example.

The final phase in our recommendations would be the application of ES and the development of neural net technologies at the level of the subcomponents of POTH2O and related units. This is perhaps the most risky application, since either the technology has had difficulties being successfully applied at this level (ES), or is novel (neural nets). Thus, the applications of advanced AI at this stage should be understood as having to begin at an earlier research phase than those at the other two steps.

Finally, we recommend that an effort be put into the development of tools through which the various suggested applications could be well implemented. While CLIPS, for example, is fine at what it does, it does not do as much as may be desirable or needed. The development of blackboard tools, object oriented tools, and better inference engines will improve the end product. Further the development of such tools may make the various applications integrate more effectively with the software of the Space Station. For example, in our discussions of how the candidates might be integrated into the the Space Stations software, we began to rely on the proposed distributed database system to perform many functions. However, this in the end might not prove to be practical. Such a database system would become overloaded if many different systems, subsystems, subsubsystems, etc each needed to put and get information from the database. This sort of argument might support the implementation of blackboards and other techniques to avoid the problem.

Thus our final recommendations are that:

- The subsystems of WRM are very good candidates for advanced automation
- The DISPLAY unit of the ECLSS support system is also a very good candidate
- ECLSSERR, although more complex, is also a good candidate
- The subsystems of POTH2O should be investigated as candidates for ES and neural nets
- The advanced automation tools for these projects should be expanded and improved.

4.0 OVERALL SYSTEM DESCRIPTION

4.1 Temperature and Humidity Control (THC)

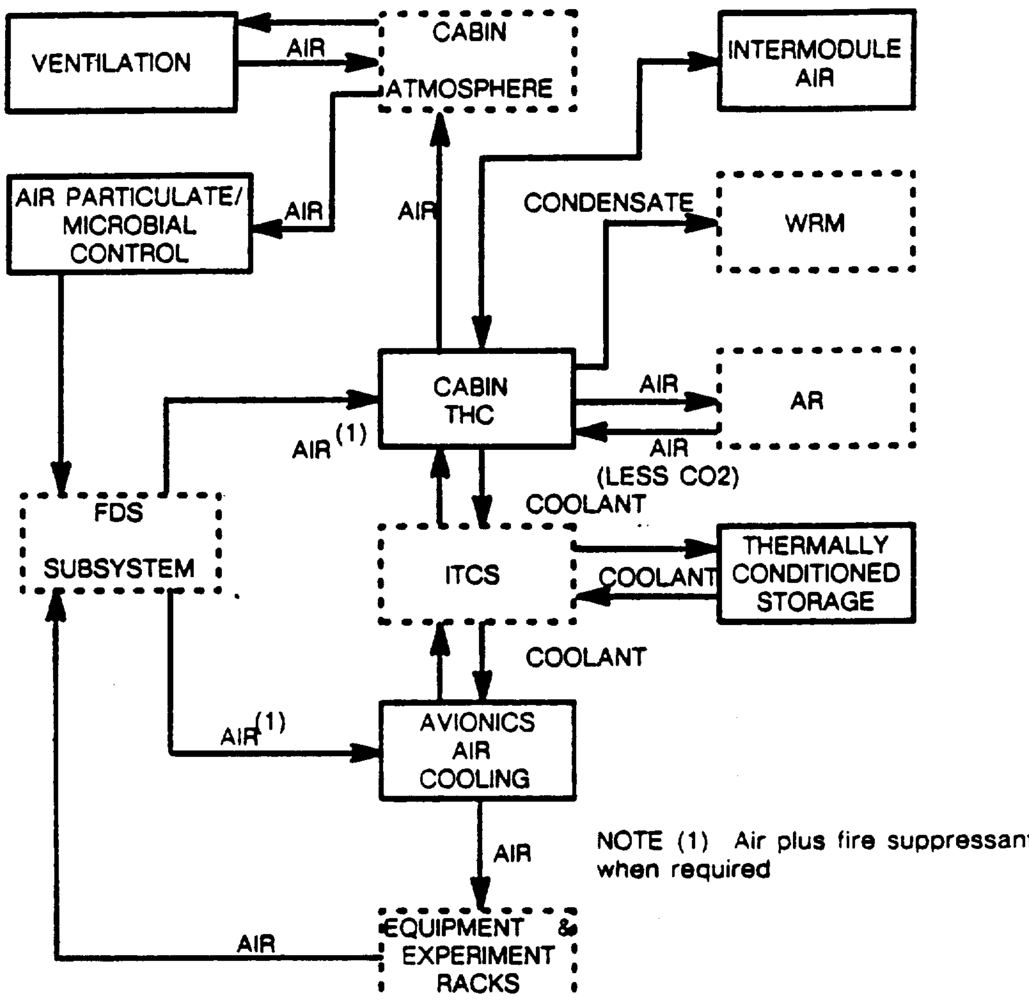
4.1.1 Subsystem Description

The THC performs three functions: 1) cabin air temperature, humidity, and ventilation control, 2) cooling of rack-mounted equipment; and 4) refrigerator/freezer provisions.[5,88,112] (See Figure 7.)

4.1.1.1 Cabin Air Temperature Humidity andVentilation Control

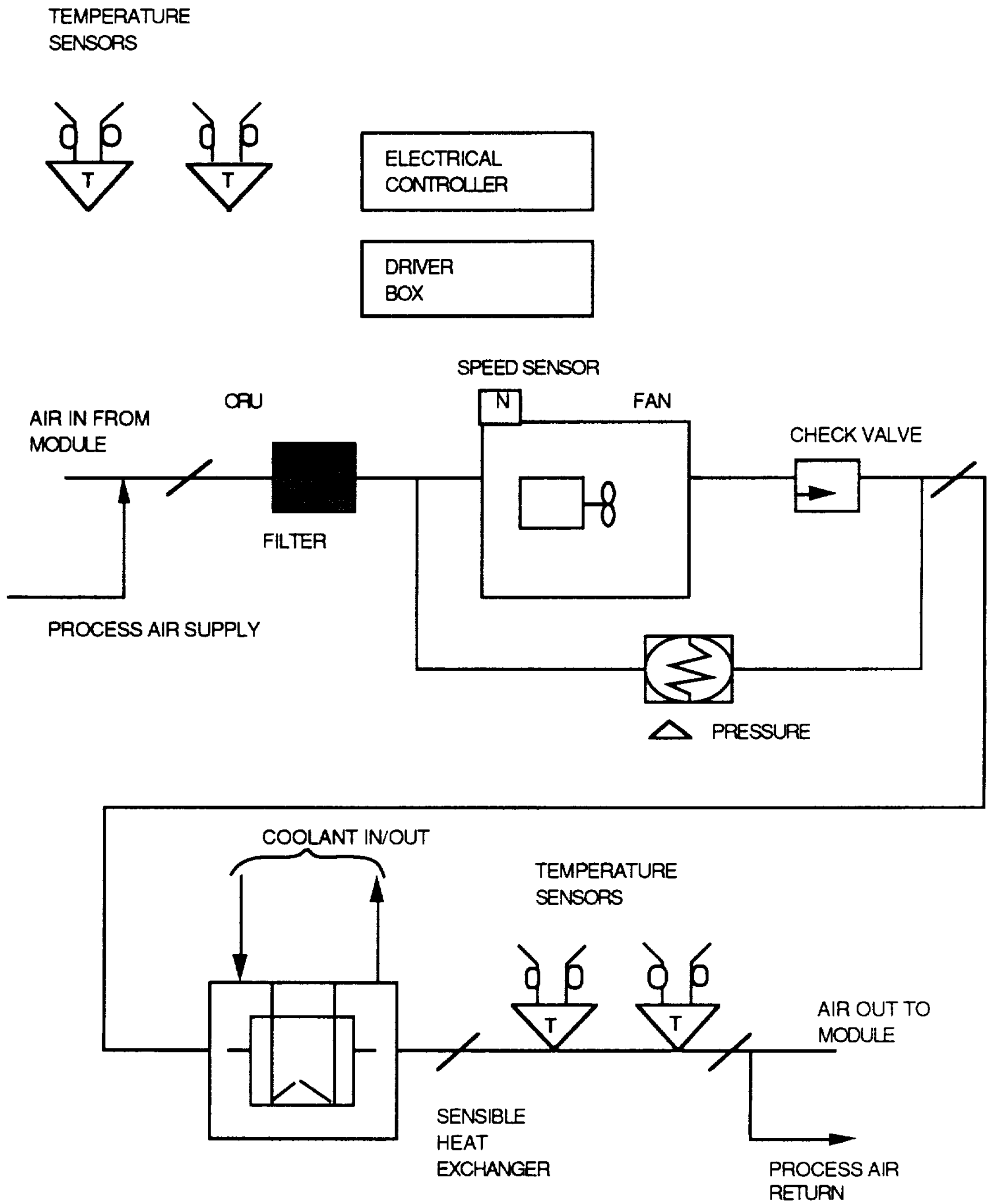
The cabin air temperature and humidity are controlled by circulating air through a condensing heat exchanger assembly. [88] A mechanical schematic of the cabin temperature and humidity control mechanism is shown in Figure 8. Ventilation provides intramodule flow rates for air that is circulated via ventilation fans within the habitable environment of the element [5] These areas include the main cabin, crew quarters, exercise facility, personal hygiene facility and wardroom. Intermodule air provides for air circulation for the respirable air that is distributed from the Habitation (HAB) module or Laboratoyr (LAB) module to the other pressurized elements.[5,88] The atmosphere for the entire station is revitalized from a centralized source. Airborne particulate and microbial removal are provided for in this subsystem.[5,88] High Efficiency Particulate Air (HEPA) and coarse filters are used to remove particulate and microbial contents to acceptable levels.[88]

The humidity control system is composed of three essential elements; the condensor, the collector and a separator/pump assembly.The condensor consists of a plate-fin heat exchanger with a four pass, cross counterflow coolant loop. The primary challenge in designing this subsystem involves gas/fluid separation in the absence of a gravity field. This separation may be accomplished on the space station with a "slurper" or rotary separator system. This system has several advantages over "elbow separator and scupper " or wick systems flown previously on the Space Transportation System (STS).[112]



Source: NASA. 1989. "Environmental Control and Life Support System Architectural Control Document," NASA Marshall Space Flight Center, February 15, 1989.[5]

Figure 7. ECLSS Temperature and Humidity Control (THC) Functional Schematic



Source: Carter, Charve. "Rack and Subsystem Level Schematics, ECLSS Subsystem Groups, and General Regenerative ECLSS Flow Diagrams", Boeing Aerospace.[28]

Figure 8. Avionics Cooling Assembly Mechanical Schematic - HAB, LAB

4.1.1.2 Avionics Air Cooling of Equipment

The air cooling equipment in the THC subsystem also provides air flow to the rack-mounted equipment for cooling and fire detection. A fan assembly produces the air flow and the air is cooled by a heat exchanger assembly which transfers the heat to the Internal Thermal Control System. Avionics air flow is supplied to racks containing power consuming equipment, and to storage racks containing combustible material.[88] A mechanical schematic is shown in Figure 8.

4.1.1.3 Thermally Conditioned Storage

Refrigerators and freezers are controlled by the THC subsystem for the purpose of food and drink storage, material and life science storage, and return of perishable items. Options being considered include the use of body mounted radiators, a vapor-compression refrigeration cycle, or a thermoelectric cooling device.[88] The Internal Thermal Control System (ITCS) removes waste heat from all internal systems including the ECLSS. The refrigerator/freezer design is a key interface that still needs to be resolved between ECLSS and ITCS.[88] The issue of liquid verses air cooling is also undecided.

4.2 Air Revitalization (AR)

The AR subsystem is responsible for the revitalization of the Space Station Freedom atmosphere so as to provide a safe and habitable environment for the crew.[5,70] It consists of four systems: regenerative CO_2 removal, CO_2 reduction, O_2 generation, and trace contaminant control and monitoring.[5,70,88] (See Figure 9). There are several competing technologies for each AR subsystem group. Computer models and comparative subsystem testing are being used to evaluate their advantages and disadvantages.[49] Oxygen and hydrogen are generated by electrolysis from hygiene or potable water. The hydrogen is combined with CO_2 in the CO_2 reduction subsystem to produce water which is delivered to the potable water reclamation subsystem.

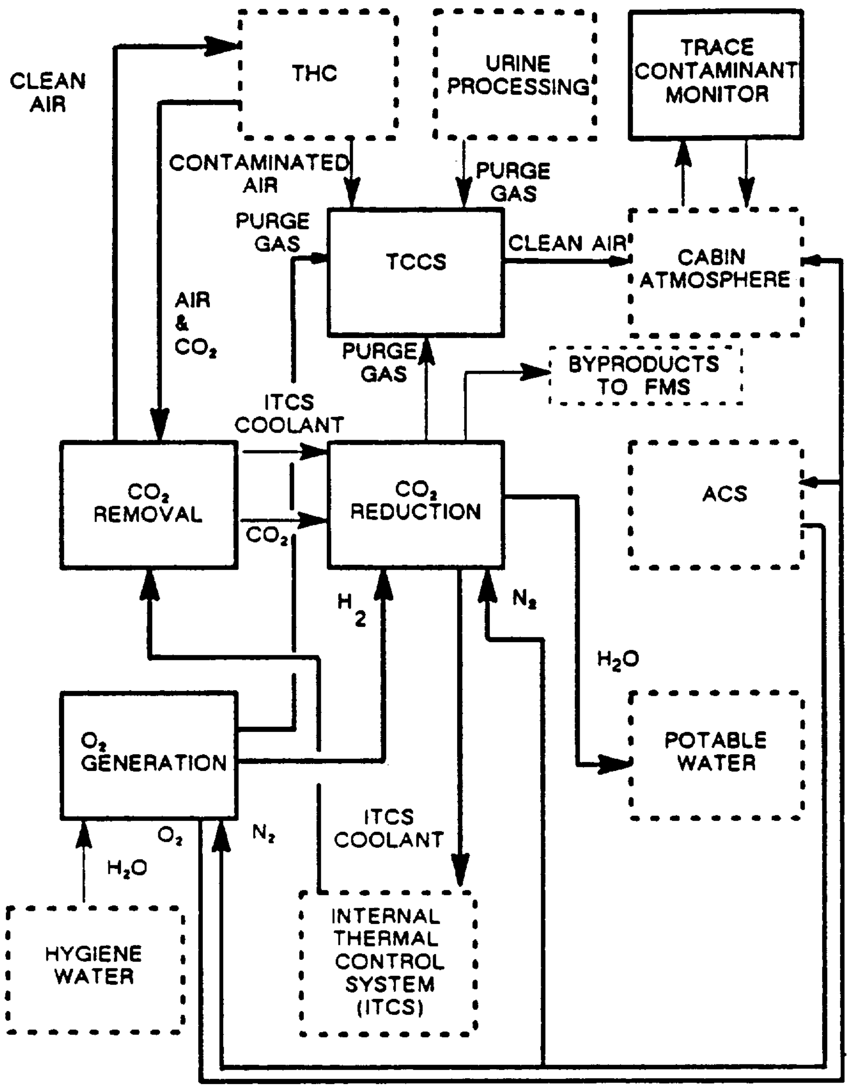
Trace contaminants are monitored and removed via the Trace Contaminant Control Subsystem (TCCS) by charcoal beds, catalytic oxidizers, and sorbent beds.[5,70,88]

4.2.1 CO_2 Removal

The CO_2 removal unit removes and maintains the control limit of metabolic CO_2 from the cabin atmosphere.[5] The CO_2 removed is concentrated from the air that has returned from the cabin and transferred to the CO_2 reduction subsystem.[49] Several technologies are being developed and tested for final selection as described below.

4.2.1.1 4-Bed Molecular Sieve (4-BMS)

The 4-BMS uses Zeolite 5A sorbent to adsorb CO_2 from the inlet air stream by trapping the molecules in voids in the crystal lattice structure of the Zeolite 5A. [49,103] (See Figure 10). This adsorption is accomplished due to molecular size, polarity of the molecules, and vapor pressure factors. Since Zeolite has a greater affinity for water, the air must be dried upstream of the CO_2 sorbent bed with a desiccant bed of silica gel and/or Zeolite 13X.[49]. The sorbents alternately adsorb and desorb CO_2, thus requiring two each of the sorbent and desiccant beds. The desorbed gas is stored in an accumulator before sending it to the CO_2 reduction subsystem.[103]



Source: NASA. 1989. "Environmental Control and Life Support System Architectural Control Document," NASA Marshall Space Flight Center, February 15, 1989.[5]

Figure 9. ECLSS Atmospheric Revitalization (AR) Functional Schematic

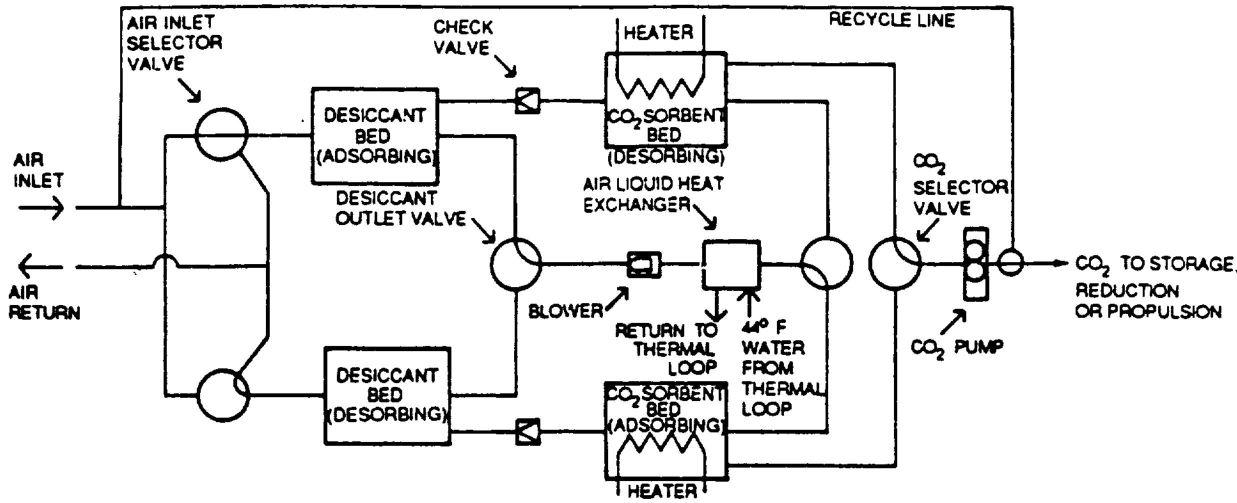


Figure 10. 4-Bed Molecular Sieve Schematic*

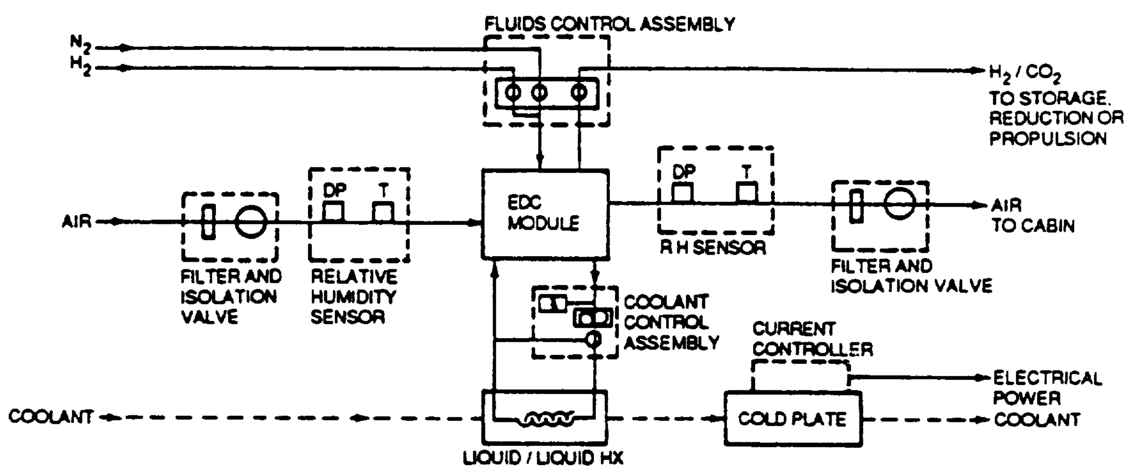


Figure 11. Electrochemical Depolarized Cell (EDC) Schematic*

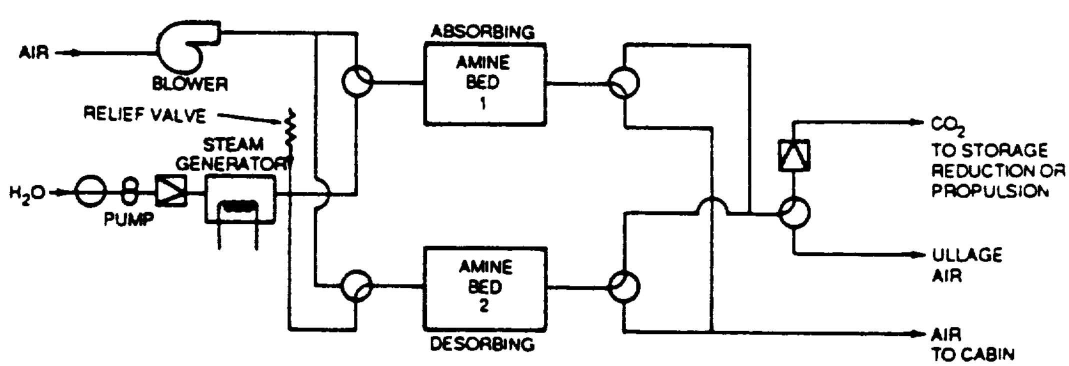


Figure 12. Solid Amine Water Desorbed (SAWD) Schematic*

*Source: Ray Ogle, Tipps, Carrasquillo, and Wieland. 1987. "The Space Station Air Revitalization Subsystem Design Concept. SAE 871448. Life Support and Environmental Branch, NASA, Marshall Space Flight Center.[49]

An independent subsystem test of the 4-BMS was performed at Marshall Space Flight Center (MSFC) in May 1987.[103] Carbon dioxide was removed from the air feed for 3 hours and samples of product concentrated CO_2 were analyzed for carbon dioxide, nitrogen and oxygen. Oxygen and nitrogen were found in the samples indicating that the sieve beds adsorbed some interstitial air along with carbon dioxide due to some leakage into the subsystem during the test. Future testing will incorporate an oxygen sensor in the CO_2 outlet line to monitor purity of CO_2.[103]

Advantages of this technology are that it can be operated independently of the other ECLSS subsystems, it does not impact cabin humidity, the sorbent materials are chemically stable and odor free and do not require regular changeout.[49] Disadvantages are the complexity of the hardware and controllers, and the relatively high weight and power requirements.[49]

4.2.1.2 2-Bed Molecular Sieve (2-BMS)

A molecular sieve sorbent made of carbon has been developed which adsorbs CO_2 in preference to water. Therefore the desiccant beds in the 4-BMS are no longer required to pre-dry the air, and only two beds of CO_2 sorbent are needed for continuous, cyclic operation.[49]

4.2.1.3 Electrochemical Depolarized Cell (EDC)

This subsystem produced by Life Systems Inc. under contract to NASA utilizes an series of electrochemical cells, each made up of two electrodes separated by a porous matrix containing an aqueous metal carbonate solution.[49] CO_2 desorbed from the air stream is transformed into carbonate and bicarbonate ions which migrate from the cathode to the anode. At the anode the CO_2 is released from low partial pressure atmospheres into a stream of H_2 and CO_2 suitable for reduction processing. (See Figure 11). The EDC is fairly light (5 to 10 lbs) and is a net producer of power (54 to 71 watts). Since the EDC is the lightest, most compact, and a net power producer, it appears to be the most desirable technology.[64]

Advantages of this subsystem are that it has the lowest weight and volume of the subsystems being considered, and as of 1987 it was nearest to flight hardware design.[49,64] Disadvantages are that it requires coupling with an H_2 source which would cause a shutdown during supply failure and which during safe haven would require a source of H_2. Also, the presence of H_2 raises safety concerns.[49] Future development includes studying a variation which can remove and concentrate CO_2 without the use of H_2.[49]

4.2.1.4 Solid Amine Water Desorbed (SAWD)

The SAWD CO_2 concentrator uses a weak base amine ion exchange resin to chemically absorb CO_2 from a mixed air stream. The amine combines with water to form a hydrated amine which then reacts with CO_2 to form bicarbonate. Steam is injected into the amine to break the bicarbonate bonds and the CO_2 is released. Since this process is cyclic, two sorbent beds are required.[49,91] (See Figure 12).

Advantages of this subsystem are that it is near flight hardware design, it has relatively low weight and power requirements, and it can operate independent of loop closure.[49] Disadvantages include significant impact from the water required for steam generation, impact on cabin humidity due to steam discharged, periodic replacement of the amine material, safety concerns of pressurized steam, and the relatively complex hardware and controllers.[49]

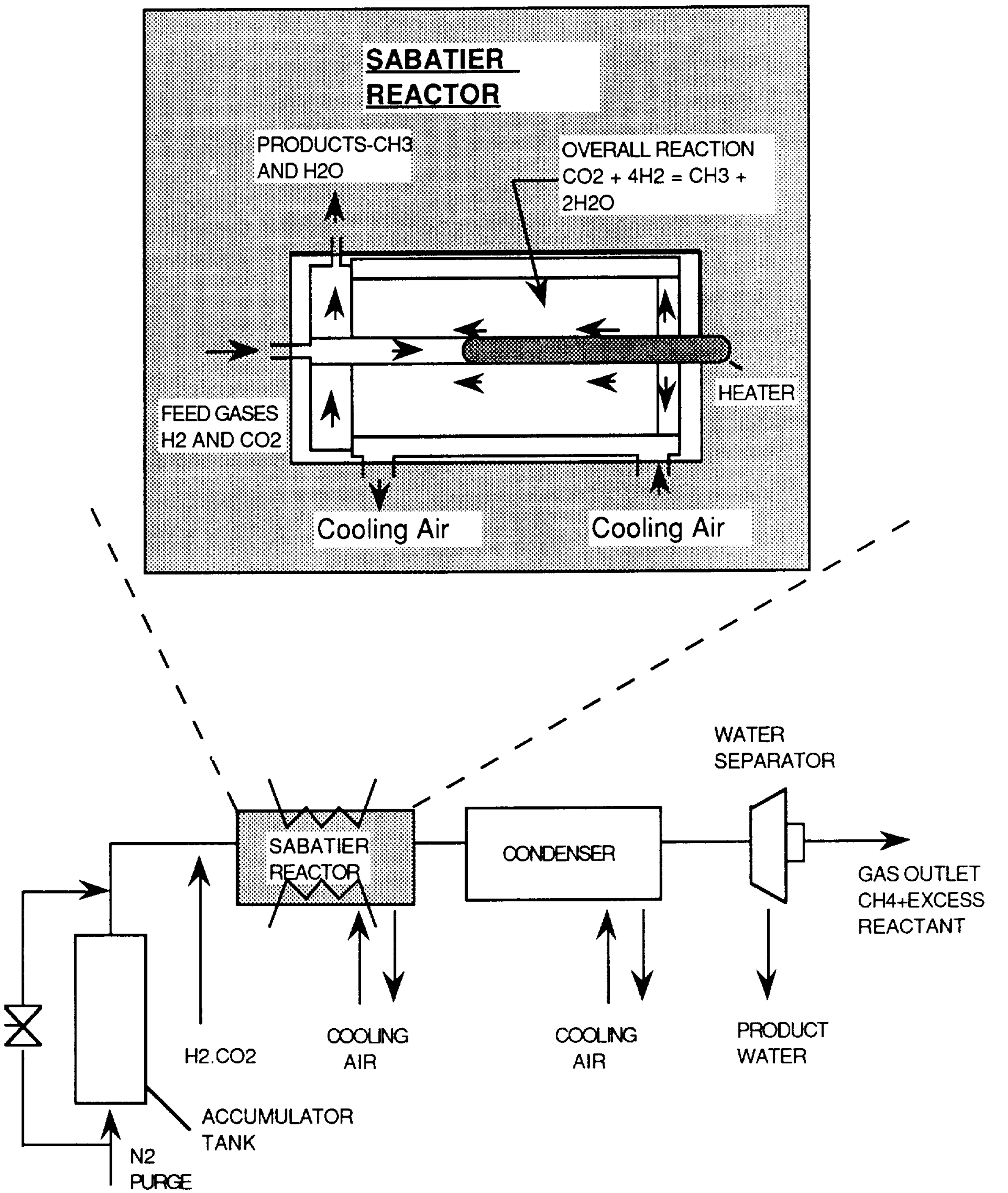
4.2.2 CO_2 Reduction

The CO_2 reduction unit utilizing hydrogen, reduces CO_2 to water and other reaction byproducts depending on the technology used.[5,49,58,89,90,97] Several technologies are being developed and tested for final selection as described below.

4.2.2.1 Sabatier CO_2 Reduction Subsystem

The Sabatier CO_2 reduction subsystem reacts carbon dioxide and hydrogen over a ruthenium on alumina catalyst to produce methane and water in an exothermic reaction.[49,103] (See Figure 13). The product water vapor is condensed and separated from the other exit gases and sent to the potable water recovery loop.[49,103] An independent subsystem test was performed in May 1987.[103] Gas and product water samples were collected and chemically analyzed. The reaction efficiency based on inlet and outlet gas was calculated to be 99.4%. During metabolic control testing in November, 1987, the reactor produced 100% of the water possible from reactant input, the separator collected and delivered 86% of this water, the cold trap another 9%, and the remaining 5% was lost with the vented methane. Overall the Sabatier successfully performed at near 100% efficiency.[91]

Advantages of the Sabatier subsystem are its high level of development, its greater reliability , its not requiring cartridge changeouts, possibly not requiring storage of products, and its easy handling of increased loads.[49] Disadvantages include the potential need for



Source: Adapted from "Water Monitoring Requirements, Current Requirements, and Subsystem Schematics"[35]; and Ray, Ogle, Tipps, Carrasquillo, and Wieland, "The Space Station Air Revitalization Subsystem Design Concept," SAE 871448, Life Support & Environmental Branch, NASA, Marshall Space Flight Center[49].

Figure 13. Sabatier CO_2 Reduction System Schematics

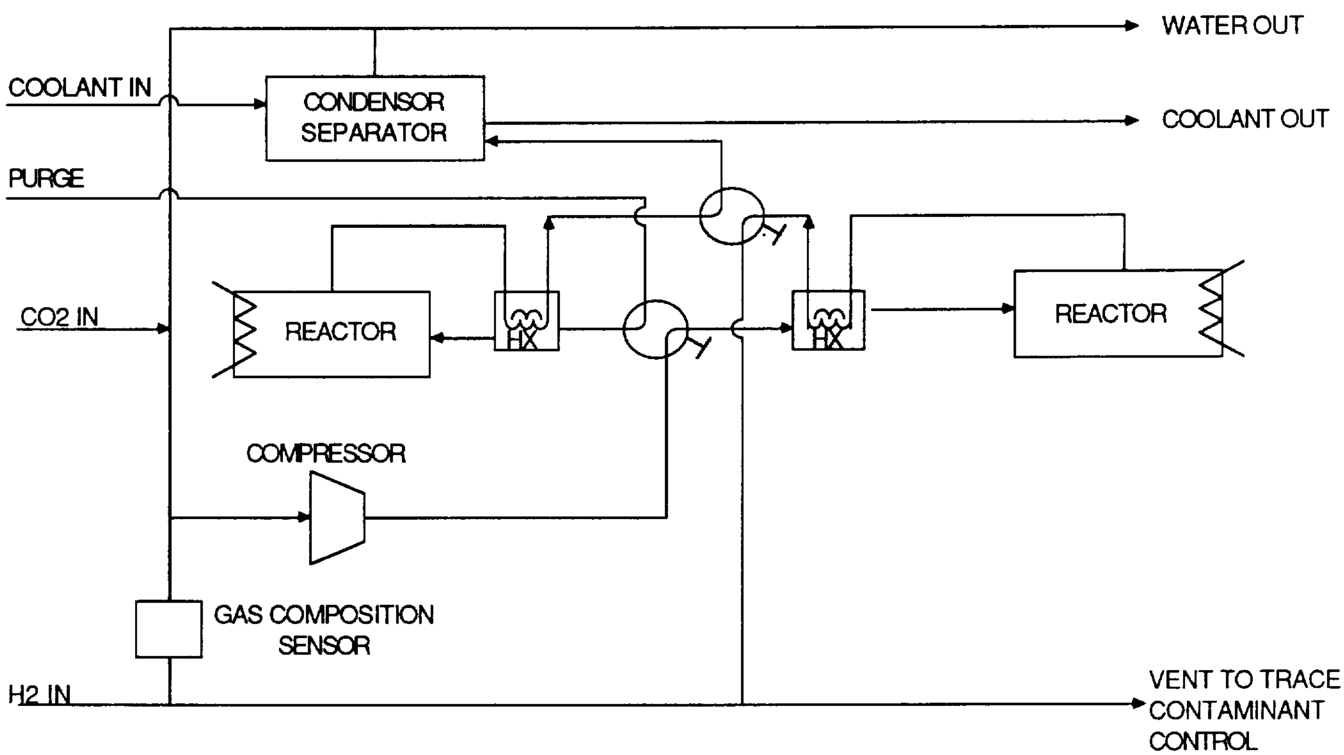
methane storage, and the loss of CO_2 due to an incomplete reaction.[49] Unless the methane produced is "recycled " by use as propellant or in fuel cells the net loss of H_2 for the station system may represent a significant resupply penalty.[89] Many concerns have been expressed for the possible negative effects of vented methane on astronomy and scientific experiments.

4.2.2.2 Bosch CO_2 Reduction Subsystem

The Bosch process is a technique for the reduction of the carbon dioxide removed from the Space Station Freedom atmosphere and the subsequent water formation for oxygen recovery. (See Figure 14). The Bosch process occurs from 426 to 726°C in the presence of a catalyst. One mole of carbon dioxide combines with two moles of hydrogen gas to produce one mole of carbon and two moles of water vapor in an exothermic reaction.[49,97] Approximately 10% of the CO_2 is reacted in each pass requiring a recirculating loop to increase the conversion efficiencies.[49,97] Unreacted CO_2 and H_2, and gaseous byproducts CO and CH_4 are continuously recycled to the inlet, while product water is condensed and separated.[49] A cold seal reactor design is used which eliminates the tremendous heat loss at the closure interface and eliminates the need for a vacuum interface. The entire process is contained within a ruggedized disposable carbon cartridge.[97] There is a recuperative heat exchanger that preheats the recycle loop gases with hot gases exiting the condenser, thus maximizing thermal efficiency. The heat exchanger has a spiral coil design which eliminates inactive areas.[97]

One of the hazards of the Bosch design was the cartridge removal. To avoid potential safety hazards an automatic N_2 purging of the carbon cartridge is done under a vacuum both before and after cartridge replacement.[97] Other components of the Bosch subsystem include a recycle loop compressor, recycle gas composition controller, vales, regulators, condensing heat exchanger, and gas/water separator. The compressor in the recycle loop controls the overall Bosch CO_2 reduction rate by controlling the recycle flow rate. The stoichiometry is controlled by measuring the volumetric H_2 concentration in the recycle loop. A zero-gravity compatible gas/water separator is used to remove the product water condensed by a heat exchanger in the recycle loop.

The Bosch system can be automatically controlled by a control monitor which incorporated microcomputer software. Computer control is used to adjust the configuration of the process when switching between operating modes, to control operating mode routines, for fault detection, fault isolation, and fault prediction, and for built-in diagnostics for subsystem verification.[97]



Source: Ray Ogle, Tipps, Carrasquillo, and Wieland. 1987. "The Space Station Air Revitalization Subsystem Design Concept. SAE 871448. Life Support and Environmental Branch, NASA, Marshall Space Flight Center.[49]

Figure 14. Bosch CO_2 Reduction Subsystem Schematic

The Bosch II prototype is currently in operation at the NASA MFSC Test Chamber. The Bosch process is reaching a level of technological maturity demonstrating its viability for application aboard Space Station Freedom.[97]

This process is promising because no on-board gaseous storage or overboard venting is required, and there is a potential for 100% efficient CO_2 recovery.[97] Aspects that still need to be addressed are optimization of power consumption, expendable weight, crew safety, and compatibility with Space Station Freedom interfaces.

Advantages of the Bosch subsystem are the high level of development, complete reduction of CO_2, compatible in zero-gravity environments, and its possible integration with the propulsion system by supplying excess H_2.[49] Disadvantages include the need to change out the cartridges and the potential risk of contamination from the low density carbon product, the longer startup time, and the higher weight and power requirements.[49,89]

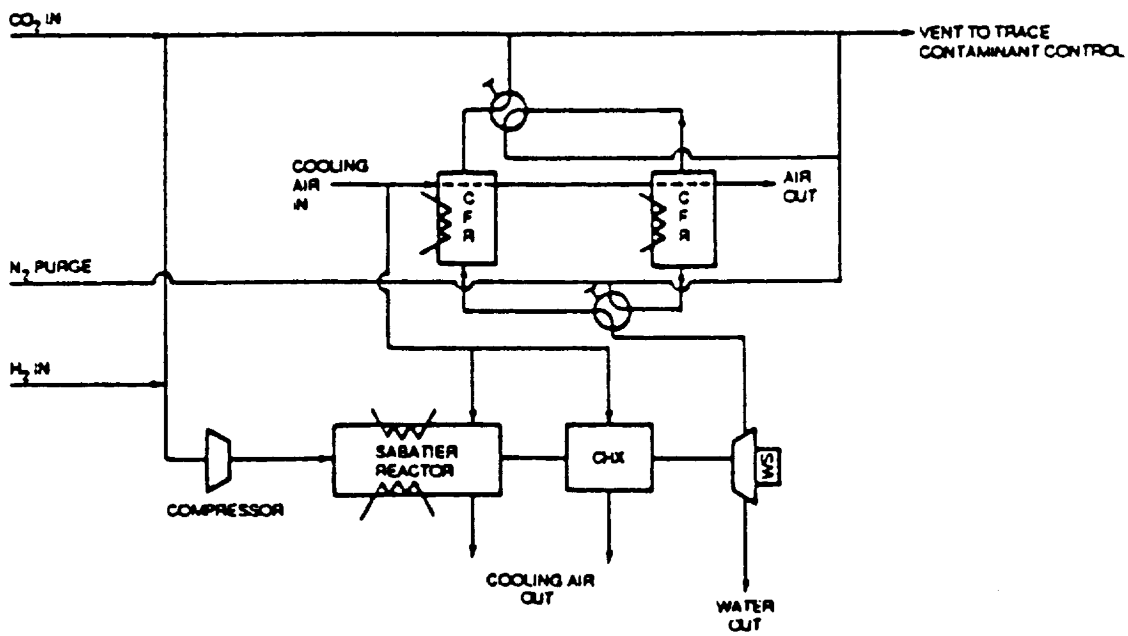
4.2.2.3 Advanced Carbon Reactor System (ACRS)

The ACRS is a combination of the Sabatier and the Carbon Formation Reactor (CFR). As in the Sabatier, carbon dioxide and hydrogen react to form methane and hydrogen gas. The methane is converted to carbon and hydrogen gas, the hydrogen is recycled, and the carbon formed is deposited inside a quartz fiber-packed reactor. Two CFR's are required for continuous operation.[49] (See Figure 15).

Advantages of the ACRS are that its dense carbon in the cartridges would be a lower contamination risk and a much less expendable volume than with those of the Bosch system, and the ACRS provides full reduction of CO_2 and excess hydrogen for potential propulsion integration.[49] Disadvantages of the ACRS are that it is the least mature subsystem requiring extensive development; it has the highest operating temperature, weight, and power requirement; and it requires cartridge changeout.

4.2.3 O_2 Generation

The O_2 Generation System generates oxygen for metabolism, leakage, and airlock replacement; and generates hydrogen for use in the CO_2 reduction unit by electrolyzing water.[5] Several technologies are being developed and tested for final selection as described below.



Source: Ray Ogle, Tipps, Carrasquillo, and Wieland. 1987. "The Space Station Air Revitalization Subsystem Design Concept. SAE 871448. Life Support and Environmental Branch, NASA, Marshall Space Flight Center.[49]

Figure 15. Advanced Carbon Reactor System (ACRS) Schematic

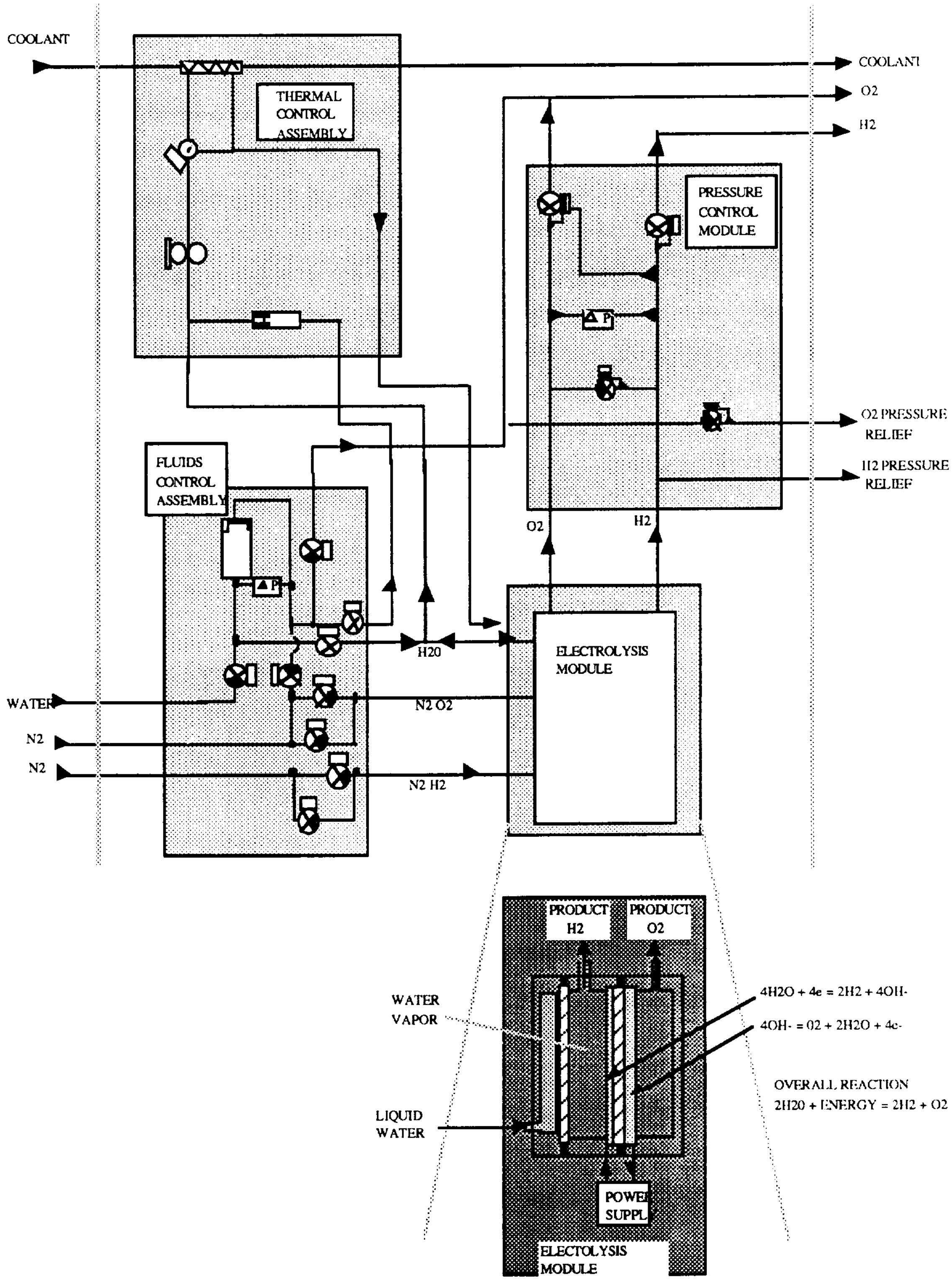
4.2.3.1 KOH Static Feed Electrolyzer (SFE)

The function of the SFE is to generate O_2 for metabolic consumption, leakage makeup, and O_2 and H_2 consumption by other ECLSS systems.[95] Water is electrolyzed in 12 cells consisting of a water feed cavity, and a cell matrix cavity that initially have equal concentrations of electrolyte.[95,103] (See Figure 16). The water and gas are separated by membranes, and the gases are separated by Potassium Hydroxide (KOH) electrolyte.[103] As electrical power is supplied to the electrodes, water in the cell matrix is electrolyzed creating a concentration gradient between the electrolyte in the water feed cavity and the electrolyte in the cell matrix. The water vapor diffuses from the water feed matrix into the cell matrix due to this gradient. Waste heat is removed by a liquid coolant controlled by a Coolant Control Assembly. A Pressure Controller maintains pressures during start-ups and shutdowns. The N_2 purge is not used during normal operation.[95] Finally, there is a Fluid Control Assembly which controls and monitors the SFE water tank fill, water feed and purge gas flows. The subsystem is controlled by micro-processor or computer-based instrumentation which provides for parameter control, automatic mode and mode transition control, automatic shutdown for self-protection, fault diagnostic functions and interfacing with data acquisition systems.[95]

Advantages of the SFE are that its simple replaceable unit design is easily maintained; its efficiency approaches 100%; its power, weight, and volume requirements are low; and the water content of the product gases are lower than it would be with a solid electrolyte.[49] Disadvantages are that the liquid electrolyte is a potential source of caustic leakage, and the cell matrix cannot withstand high differential pressures requiring careful control of cell cavity pressure.[49]

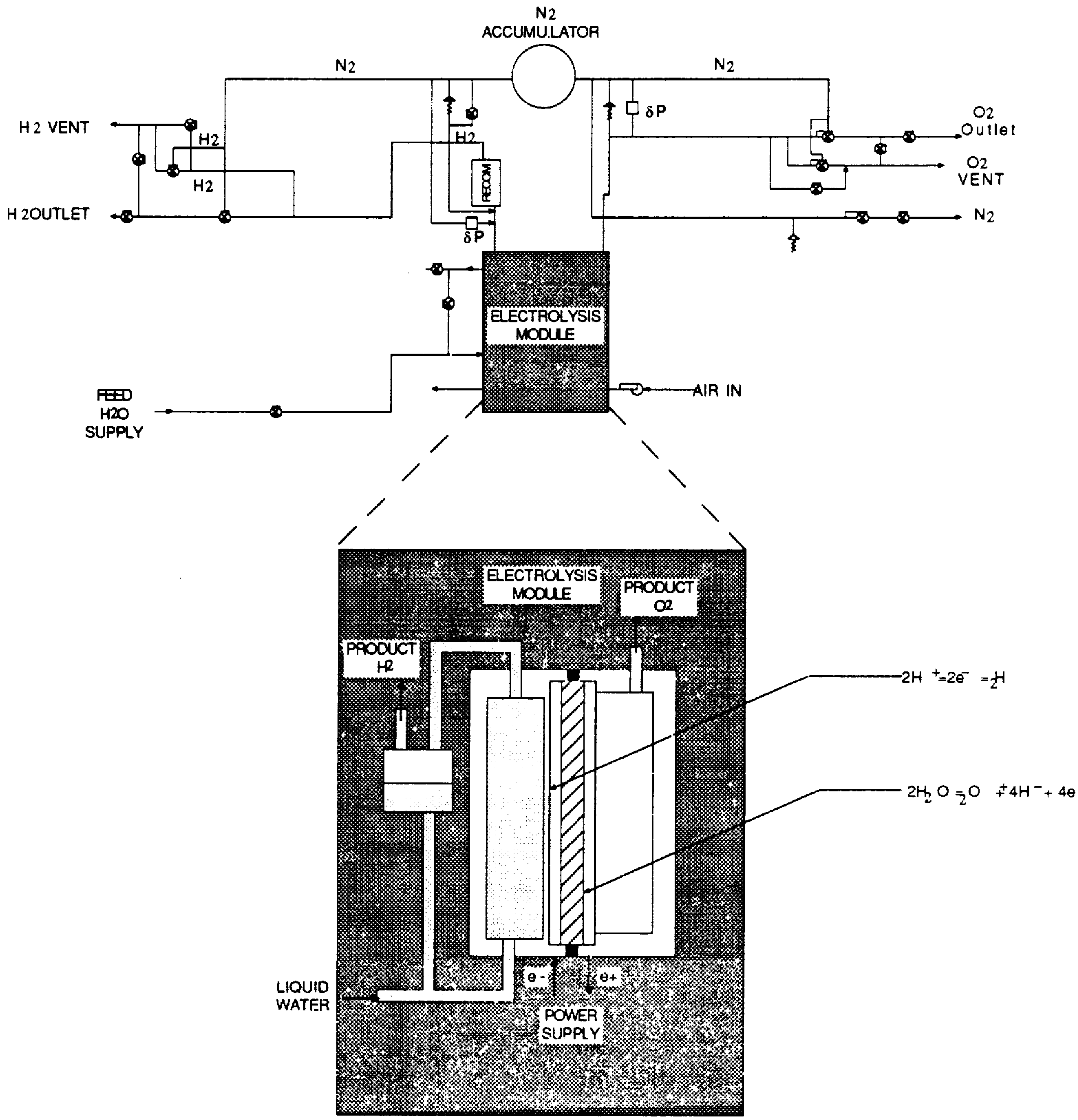
4.2.3.2 Solid Polymer Electrolyte (SPE)

The SPE separates water from the hydrogen compartment by a vapor permeable membrane. When power is supplied, the water is converted to O_2 at the anode. A water concentration gradient is set up within the electrodes and the solid polymer electrolyte.[49] Solid Polymer Electrolyte (SPE) O_2 generation by water electrolysis became practical in the late sixties with the introduction of fluorocarbon ion exchange membranes. Developed by Hamilton Standard under contract to NASA, the SPE vapor feed electrolizer is capable of supplying 0.06 lbs./hr. of O_2 at 3000 psi. A design used in nuclear submarines was modified to eliminate rotating equipment, the pre-deionizer, and associated maintenance. The design uses the energy in the high pressure hydrogen produced within the electrolyzer to pressurize the input process water 3000 psi. without the use of a mechanical pump.[60] (See Figure 17).



Source: NASA. 1989. "Environmental Control and Life Support System Architectural Control Document," NASA Marshall Space Flight Center, February 15, 1989.[5]

Figure 16. KOH Static Feed Electrolyzer (SFE) Schematic



Source: NASA. 1989. "Environmental Control and Life Support System Architectural Control Document," NASA Marshall Space Flight Center, February 15, 1989.[5]

Figure 17. Solid Polymer Electrolyte (SPE) Schematic

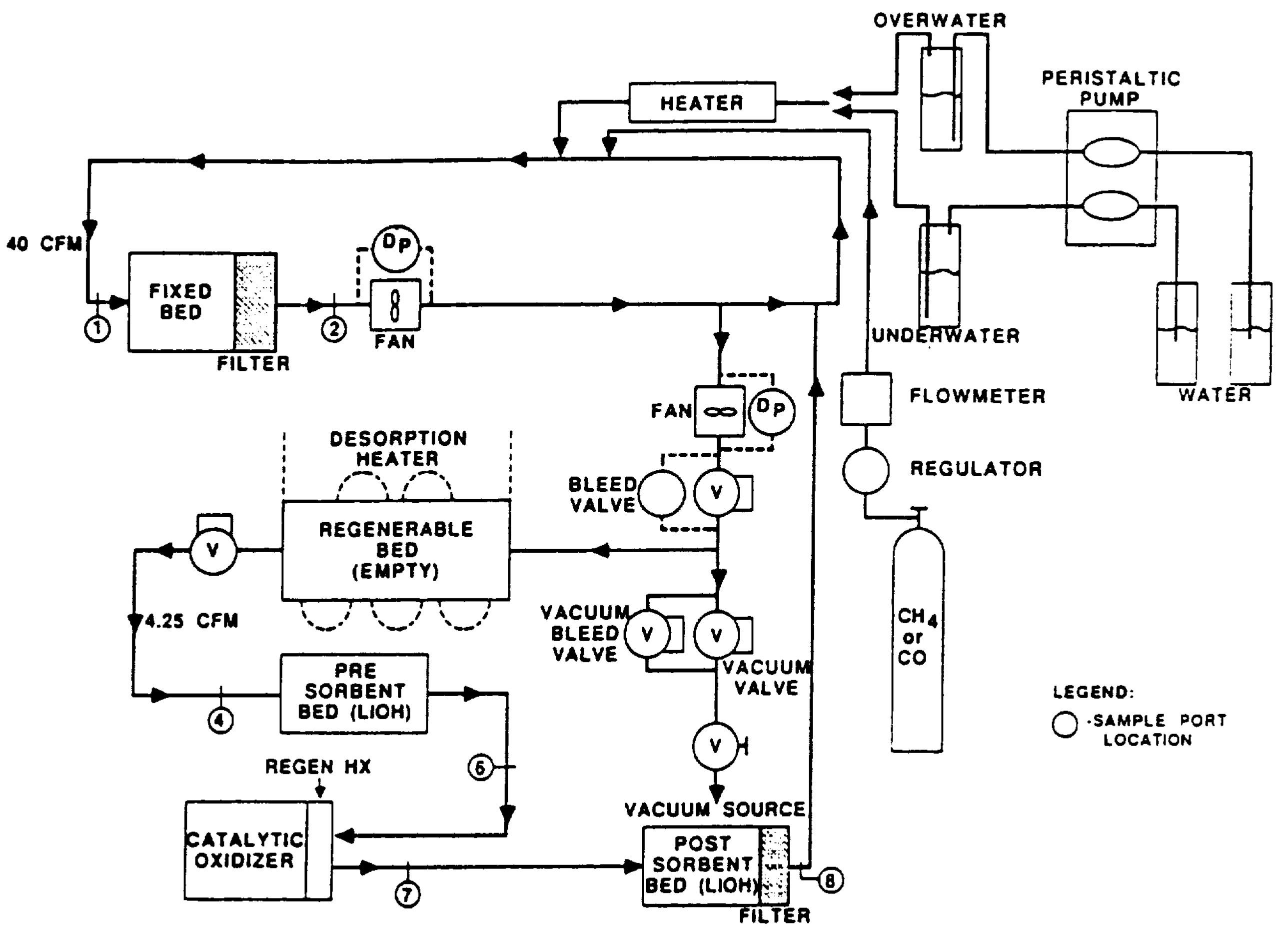
Advantages of the SPE are that the acid electrolyte is immobilized in the membrane, it contains no hazardous liquids, and its membrane exhibits high strength which can withstand high differential pressures. Disadvantages include its lower efficiency than the alkaline subsystems, and the higher vapor content of its product gases.[49]

4.2.4 Trace Contaminant Control Subsystem (TCCS)

The TCCS will remove trace contaminants and odors from the cabin atmosphere.[5] Several options currently in design include a fixed bed with charcoal and sorbents for removal of specific contaminants, a high temperature catalytic oxidizer with pre- and post-sorbent beds, and a low temperature carbon monoxide oxidizer.[49] (See Figure 18).

4.2.4.1 High Temperature Catalytic Oxidation
1. Expendable Adsorbers
    a) Carbon Adsorbers
    b) Acid Gas Adsorption
2. Regenerative Adsorbers
    a) Carbon Adsorption
    b) Acid Gas Adsorption

4.2.4.2 Sequential Catalytic Oxidation
1. Expendable Adsorbers
    a) Carbon Adsorbers
    b) Acid Gas Adsorption
2. Regenerative Adsorbers
    a) Carbon Adsorption
    b) Acid Gas Adsorption



Source: Ray Ogle, Tipps, Carrasquillo, and Wieland. 1987. "The Space Station Air Revitalization Subsystem Design Concept. SAE 871448. Life Support and Environmental Branch, NASA, Marshall Space Flight Center.[49]

Figure 18. Trace Contaminant Control Subsystem (TCCS) Potential Design

4.2.5 Trace Contaminate Monitor

Contamination monitoring equipment monitors trace contaminants that are present as vapor or gases and total particulate levels in the cabin atmosphere.[5,59,77,82]

We have been unable to identify a particular system baselined for station ECLSS use. There are several relatively mature technologies available and development in this area may be low priority. The CAMS I system (Central Atmospheric Monitoring System) was developed for the space program and is currently used on US submarines. This instrument consists of a mass spectrometer and nondispersive infrared analyzer (FTIR) which simultaneously monitors eight gaseous contaminants. CAMS II is in final development and will monitor 12 preselected contaminants, including refrigerants and hydrocarbons, using a scanning mass spectrometer in conjunction with a photoionization detector. A similar system is likely to be adapted to station use.[82]

4.2.6 Particulate Control

Cleanliness requirements for the Space Station Freedom require that the particulate/microbial contamination load be controlled. The following are descriptions of some technique being considered for this control.

4.2.6.1 High Efficiency Particulate Air Filters (HEPA)

HEPA's are 99.97% efficient in filtering particles 0.3 micrometers or larger in size. Coarse filters are used prior to the HEPA's to reduce clogging. Advantages of the HEPA filters are that they are the only method capable of meeting the Space Station Freedom cleanliness requirements as a stand alone method, and that they filter in the sub-micrometer size range.[49] Disadvantages are that they have a relatively high energy requirement and their efficiency depends on appropriate air flow being supplied.[49]

4.2.6.2 Negative Ionization Electrostatic Precipitation

Negative-ionization electrostatic precipitation has been used in nuclear submarine closed environments to remove particulates.[49] This method is highly effective for particles in the 0.1 to 10 micrometer range, has a relatively low pressure drop, and has the potential for reuse. Disadvantages are that it requires relatively high energy inputs, and uses high voltages which can possibly produce ozone and electromagnetic interference.[49]

4.3.6.3 Ultraviolet Radiation

Ultraviolet radiation is effective in killing airborne microbes including yeasts, molds, bacteria, rickettsiae, mycoplasma, and viruses.[49] Disadvantages of this method are the potential of UV radiation exposure to the crew, the possibility of ozone production, and mercury release in the event of lamp breakage.[49]

4.3 Atmospheric Control and Supply (ACS)

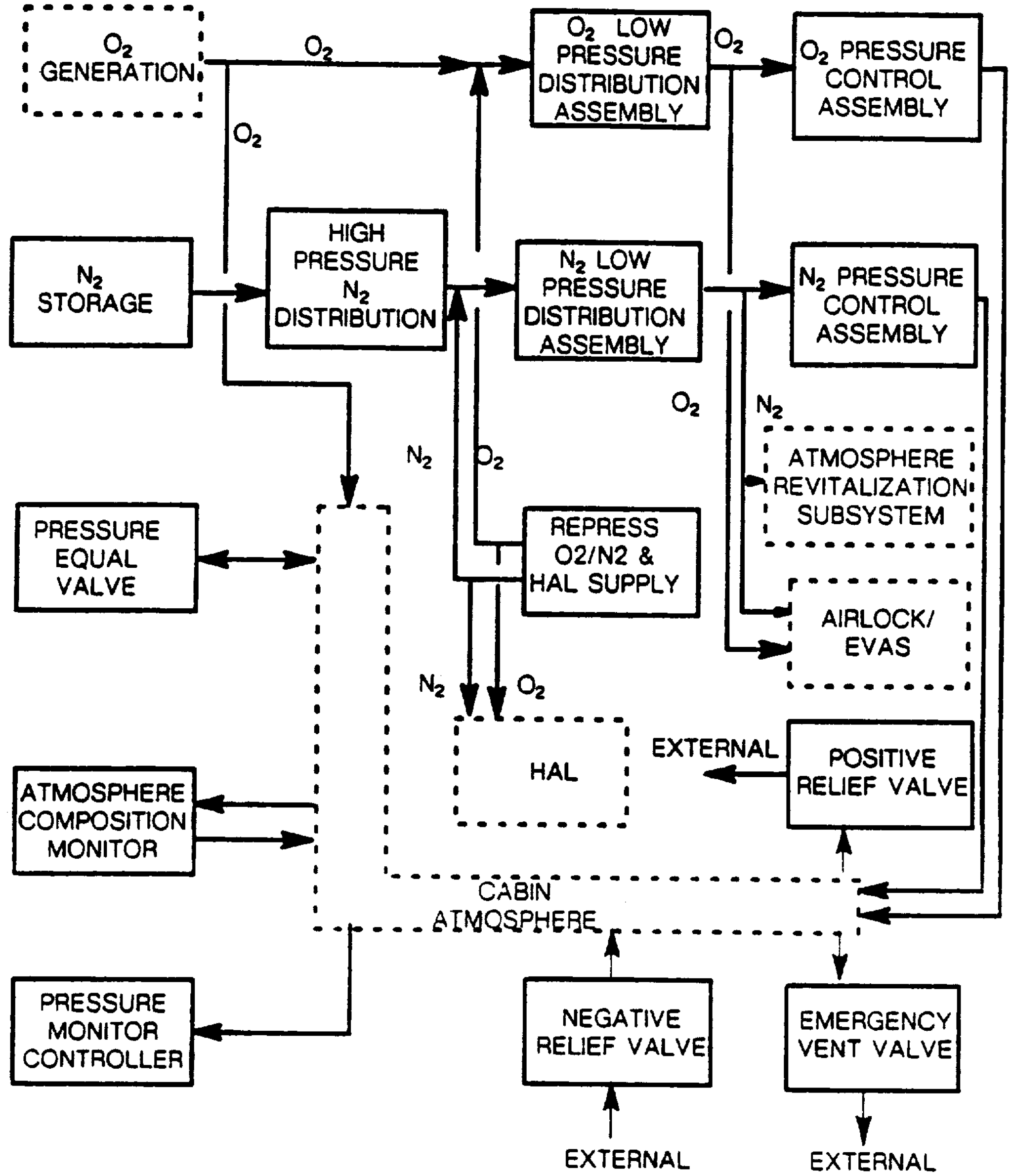
The ACS subsystem is responsible for the regulation and control of total pressure, oxygen partial pressure, and gas composition for all pressurized elements of the Space Station Freedom.[5,70,88] The ACS provides an internal environment to support and maintain crew comfort, convenience, health and well being by keeping the respirable atmosphere within certain requirements.[88] It's functions also include accommodation of: atmospheric leakage of each module at a maximum of 0.23 KG/day with an overall station maximum of 2.27 KG/day, experiment vent, airlock losses, and pressure vent and relief capability. This subsystem contains the oxygen and nitrogen storage and resupply tanks for atmospheric makeup, repressurization, hyperbaric chamber operations, and O_2/N_2 distribution equipment throughout the pressurized elements.[5,88] See Figure 19 for the ACS functional schematic.

4.3.1 O_2/N_2 Pressure Control

O_2/N_2 pressure control regulates the composition of the atmosphere for the modules, resource nodes, airlock and hyperbaric airlock atmosphere. It also maintains the total pressure. The atmospheric pressure control maintains the internal pressure at 14.7 plus or minus 0.2 psia for the station and for any pressurized element independent of the rest of the station. If any single element loses its atmosphere unexpectedly, emergency repressurization is invoked to restore the station to operational status. During hatch opening and closing, pressure equalization is provided by equalization valves. Airlocks are operated from 14.7 to 0 to 14.7 psia during exit and entry from space. Pressurization for the hyperbaric chamber is used to treat bends or air embolism and requires rapid increase in the hyperbaric chamber pressure.[5,56]

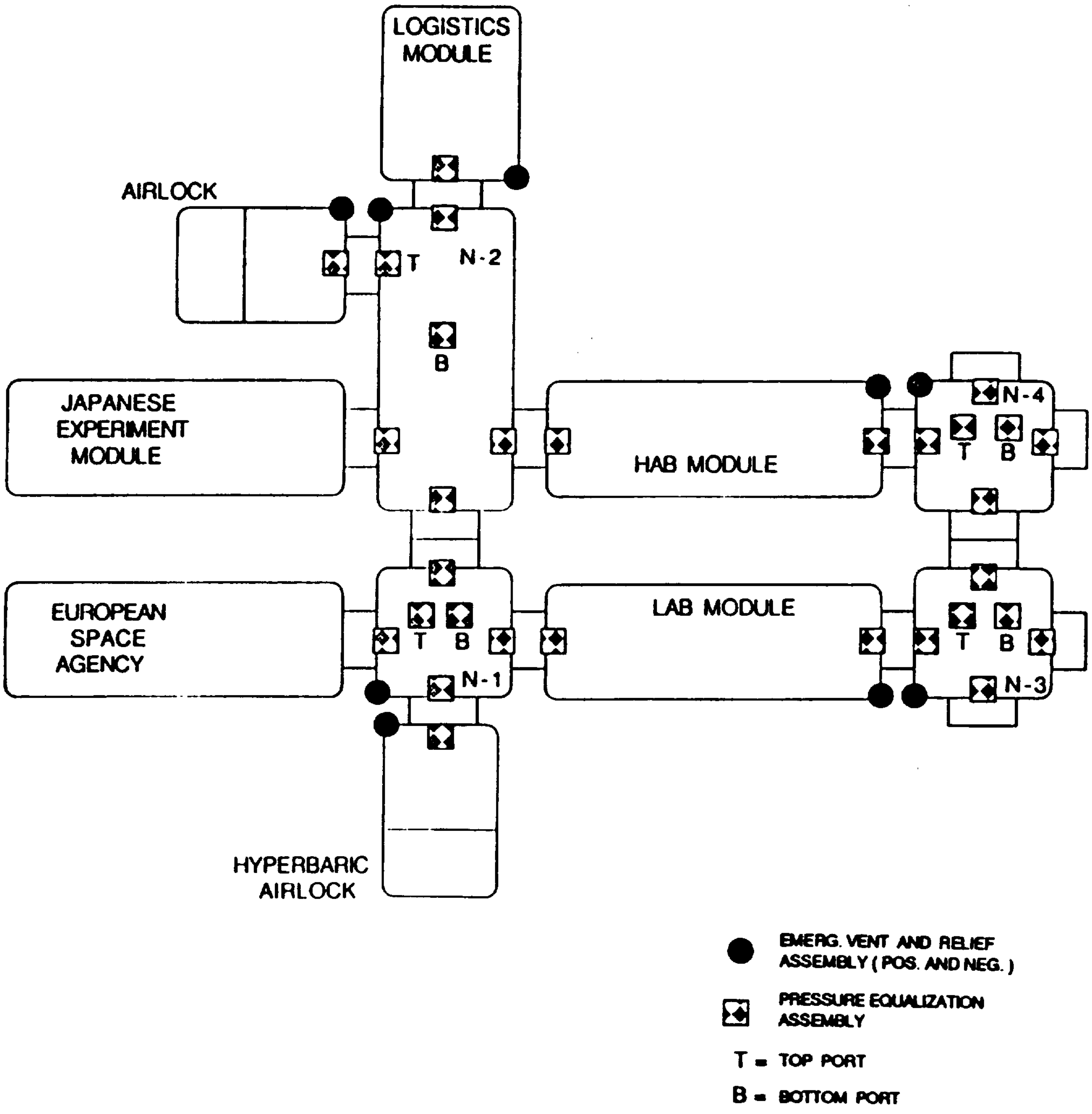
4.3.2 Vent and Relief

Vent and relief hardware provides for the capability to avoid over or under pressure conditions, depressurize habitable volumes, equalize pressures between modules, and permit the transportation of pressurized volumes from the ground to orbit.[5] A schematic of the vent and relief assembly and pressure equalization is shown in Figure 20.



Source: NASA. 1989. "Environmental Control and Life Support System Architectural Control Document," NASA Marshall Space Flight Center, February 15, 1989.[5]

Figure 19. ECLSS Atmosphere Control and Supply (ACS) Functional Schematic



Source: Carter, Charve. "Rack and Subsystem Level Schematics, ECLSS Subsystem Groups, and General Regenerative ECLSS Flow Diagrams", Boeing Aerospace.[28]

Figure 20. Vent and Relief Assembly and Pressure Equalization Schematic

4.3.3 O_2/N_2 Storage

$O2/N_2$ storage tanks provide oxygen and nitrogen for the repressurization of a single pressurized element, plus one operating cycle of the hyperbaric chamber. N_2 storage tanks provide nitrogen atmosphere makeup.[5]

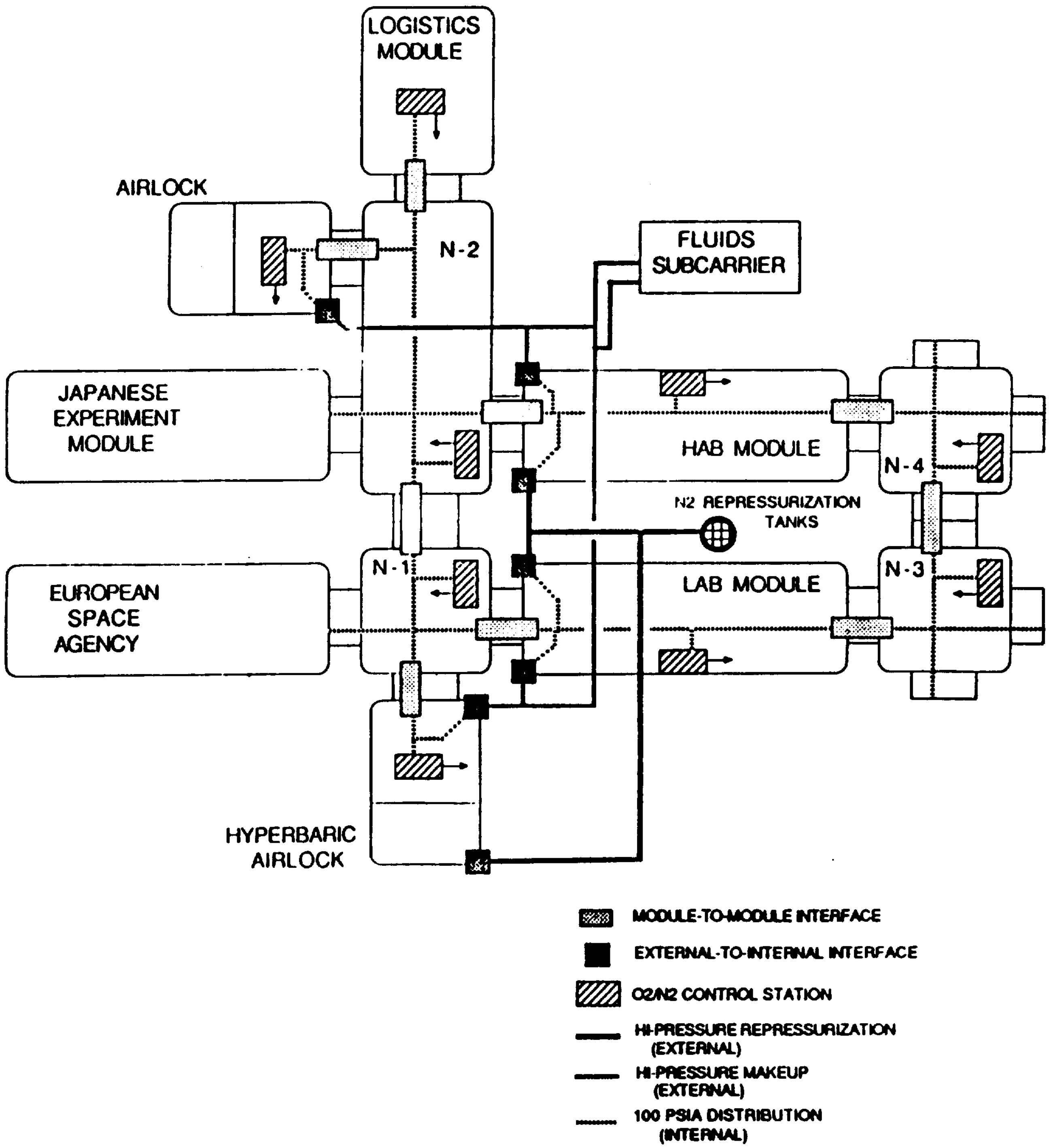
4.3.4 O_2/N_2 Distribution

O_2/N_2 distribution plumbing consists of internal/external lines, valves and quick disconnects to facilitate the integration of subsystem components.[5] A schematic of the nitrogen distribution system is shown in Figure 21.

4.3.5 Atmosphere Composition Monitoring

In addition to trace contaminant monitoring functions mentioned in earlier sections on the ARS, a O_2 partial pressure sensor will provide O_2 partial pressure information for makeup gas balancing. The Zirconia sensor block has two electrode systems, one across a ambient gas filled chamber and one with PdO paste. Galvanometric and Voltametric measurements across these junctions provide for self correction/calibration of the sensor. [76]

An improved pressure decay sensor and pressure balanced latching valve are under development to provide improved automatic control of atmosphere composition.[112]



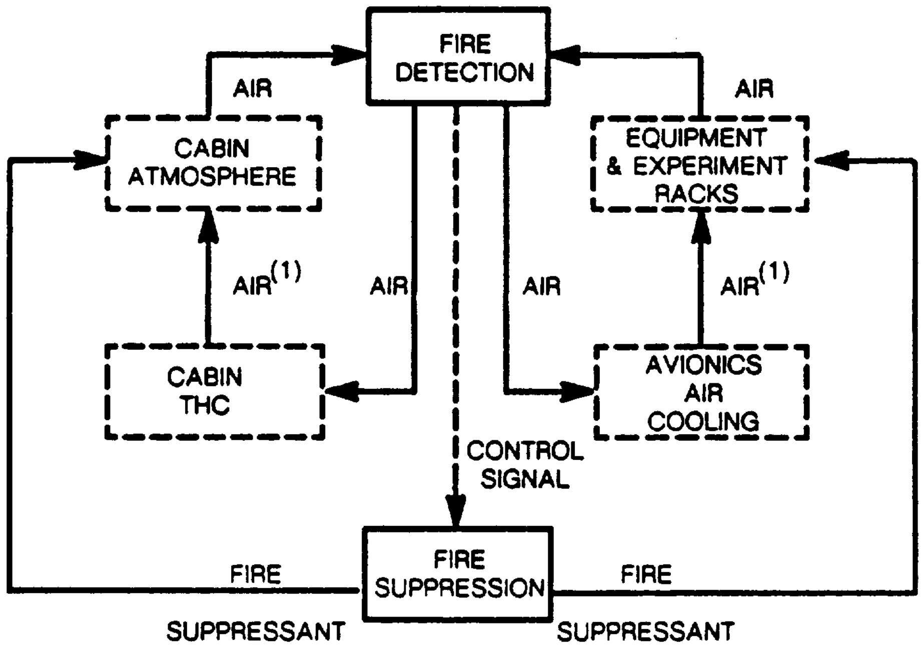
Source: Carter, Charve. "Rack and Subsystem Level Schematics, ECLSS Subsystem Groups, and General Regenerative ECLSS Flow Diagrams", Boeing Aerospace.[28]

Figure 21. ECLSS Nitrogen Distribution Schematic

4.4 Fire Detection and Suppression (FDS)

The FDS subsystem comprises hardware that detects and suppresses fires within the pressurized elements of the Space Station Freedom.[5,88] Sensors are being tested that can detect fires in the four stages of combustion: incipient, smoldering, flame and heat. (See Figure 22.) Ionization detectors, infrared/ultraviolet sensors, and thermal sensors are being considered. Fire suppression consists of the tanks and distribution system that supply the fire suppressant to equipment racks and standoffs, and portable extinguishers for manual fire suppression.[5] Fires are first located, their magnitude determined, and then they are isolated. Isolation is first performed at the rack level by cutting off airflow through the rack, releasing suppressant into the rack, and removing power from the rack. Second, if needed, the intermodule airflow is shut off, hatches are closed, and the module atmosphere is vented to space.[5] Either CO_2 or Halon 1301 will be used as the primary fire suppressant. The Halon 1301 is better for flammable liquid and electrical fires. CO_2 however provides better cleanup in a closed environment situation.[88]

A Quartz Crystal Microbalance (QCM) sensor was originally proposed for STS use[113] but stability and calibration problems forced development of an alternative. An active ionization detector using Am 241 was produced to detect submicron pyrolitic matter. This fire sensor technology has proven stable and reliable for STS use and it is anticipated that a similar design will be used for the station.



NOTE (1) Air flow shall cease upon fire detection and release of fire suppressant.

Source: NASA. 1989. "Environmental Control and Life Support System Architectural Control Document," NASA Marshall Space Flight Center, February 15, 1989.[5]

Figure 22. ECLSS Fire Detection and Suppression (FDS) Functional Schematic

4.5 Waste Management (WM)

The WM subsystem processes and stores fecal matter and other associated wastes.[88] There are three main subsystems; urine collection, fecal collection and processing, and return waste storage.[107]

The STS waste management has required some redesign work[11] and recent improvements have generally been successful in handling this waste while meeting crew hygiene and asthetics requirements. Since compacted fecal waste will be returned from the station, STS technology may be directly applicable for this subsystem. No information was available on new development work in progress.

4.6 Water Recovery and Management (WRM)

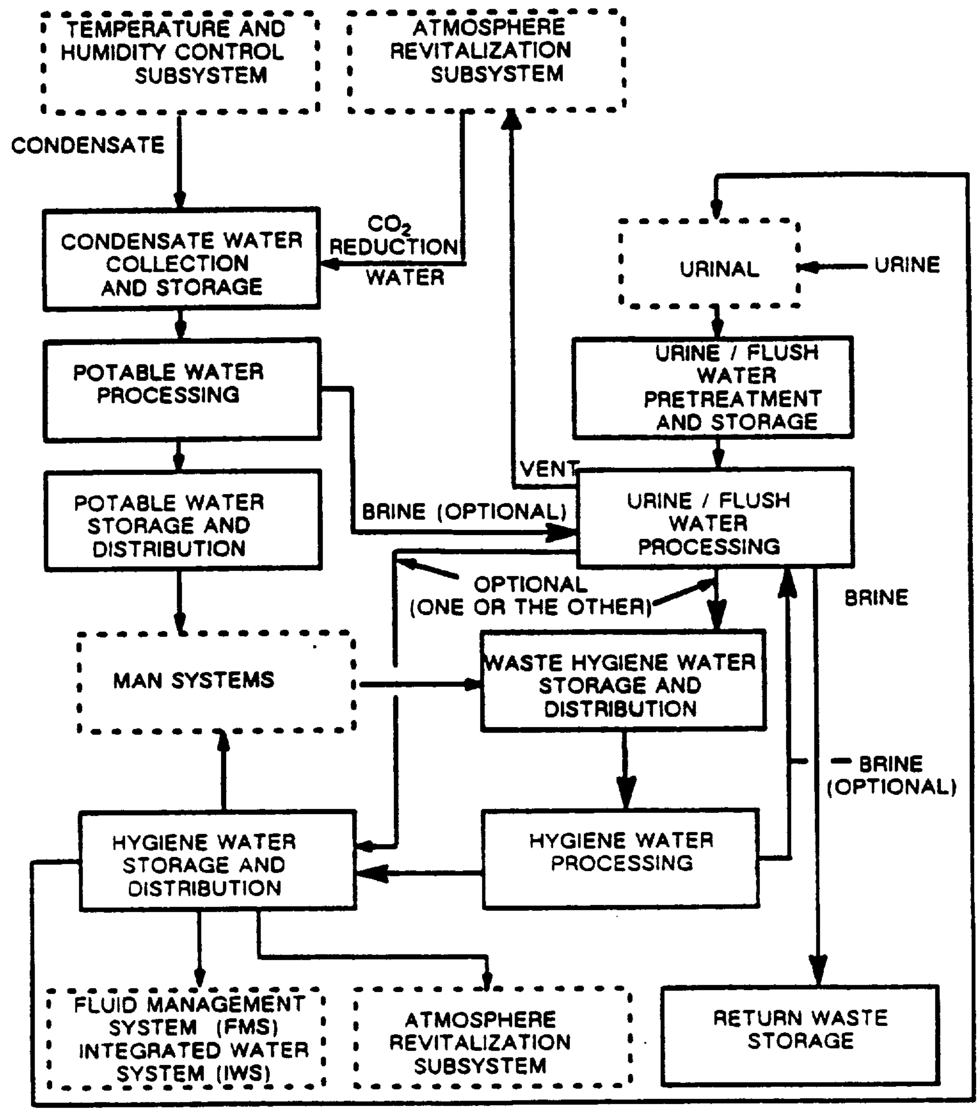
The main function of WRM is to provide a safe reliable supply of water to meet Space Station Freedom needs, while minimizing water-related resource requirements.[44] The WRM subsystem includes processors that reclaim water from various waste water sources (both within the ECLSS as well as other Space Station Freedom systems such as Man Systems, health maintenance, propulsion, and transportation systems), and distributes the reclaimed water to the U.S. modules, nodes, airlock, hyperbaric chamber, and logistics module. It also monitors the water distribution system for microbial and chemical contamination, thermally conditions water, and stores water. Two grades of water are produced: hygiene water and potable water.[88,44] (See Figure 23.)

4.6.1 Potable Water System

The Potable Water system is functionally centralized, with two units located in each of the U.S. modules. Four units are needed to satisfy the safe haven safety-critical function. This means that if there were two non-repairable failures and/or a loss of either of the U.S. modules, then they would have to meet a fail-operational/fail-safe/restorable criteria.[5,44,88] Potable water is the grade of water that is used for crew ingestion, oral hygiene, food preparation, Health Maintenance Facility uses, and portable emergency provision.[5] It is produced by the reclamation of humidity condensate collected from the cabin atmosphere and product water from CO_2 reduction.[44,88] Potable product water is checked for safe water quality parameters and stored prior to use. This system is described in detail in Section V.

4.6.2 Hygiene Water System

Hygiene water is used for non-ingestive crew activities such as handwashing, showers, dishwashing, laundry, urinal flushing, and O_2 generation.[5] The Hygiene water system is also functionally centralized, but only requires two units since it is not considered a safety critical system. One unit is located in each U.S. module.[44] Hygiene water is produced by reclaiming water from the Man Systems such as urine, shower, handwashing, dishwashing, and clothes washing.[88] The system hardware includes pre/post treatment, processing, and product quality monitoring which is described in later sections.[5]



Source: NASA. 1989. "Environmental Control and Life Support System Architectural Control Document," NASA Marshall Space Flight Center, February 15, 1989.[5]

Figure 23. ECLSS Water Recovery and Management (WRM) Functional Schematic

Product water from the hygiene reclamation system in checked for water quality parameters and stored. Product hygiene water is used in the Man Systems as well as in oxygen generation in the ARS subsystem, and for urinal flush water in the WM subsystem.

4.6.3 Urine Water Recovery

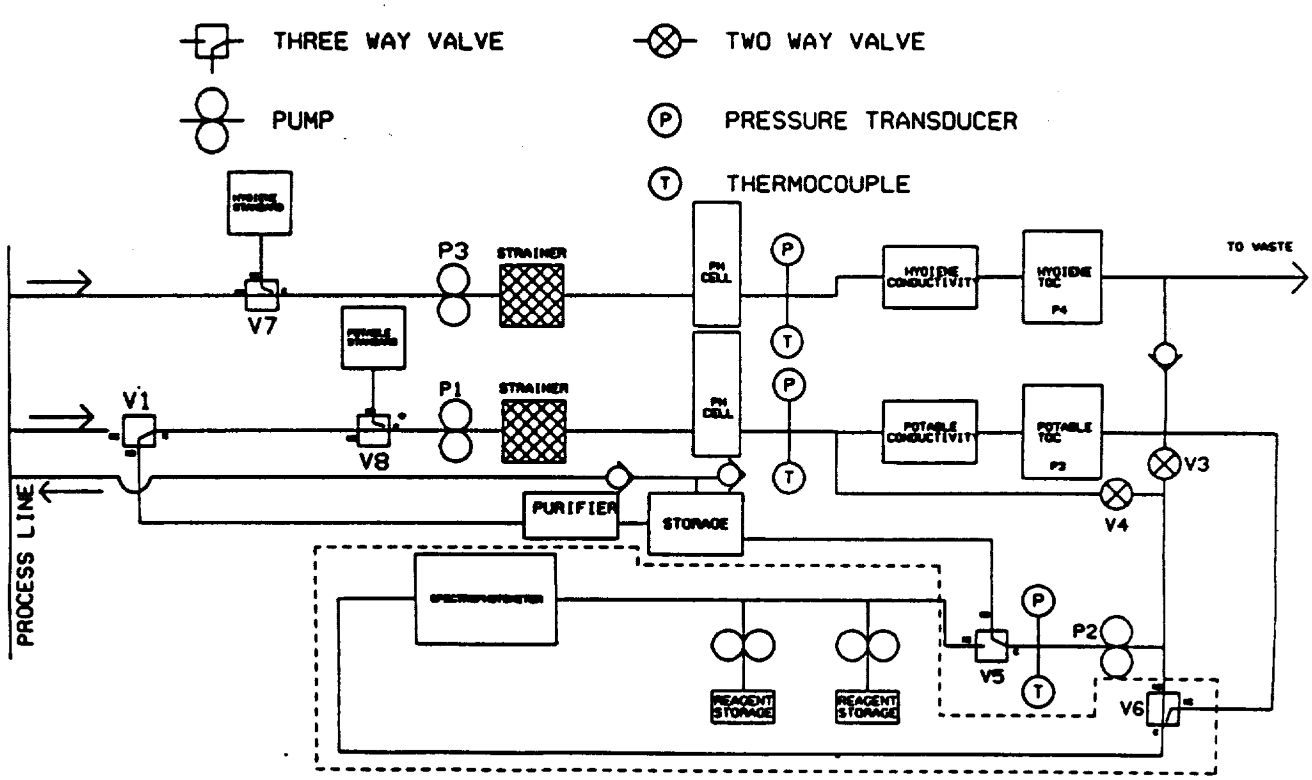
The urine reclamation is accomplished in a separate process from the other reclamation processes.[44] It provides for the extraction of water from urine/flush water and includes the hardware for pretreatment, processing, product quality monitoring, and storage of concentrated brine.[5] Specific competing technologies are described in later section 4.6.5. It is necessary to pretreat urine prior to distillation to fix free ammonia, inhibit microbial growth, control odor, and reduce foaming. Several oxidizing and non-oxidizing pretreatments are being considered; including oxone, $CuSO_4$, hydrogen peroxide, and several proprietary surfactants.[52]

4.6.4 Water Quality Monitor

Boeing produced a schematic for a Water Quality Monitor "ADP EC-3" in May 1988.[35] (See Figure 24). It includes streams from the process line going through strainers, pH and TOC meters, and finally spectrophotometric analysis.

The current technology under evaluation for Total Organic Carbon (TOC) analysis is based upon ultra-violet absorption. It can handle extremely low levels (0.02ppm) on a continuous basis, and the sample is totally unchanged after exiting the unit.[94] Previous technologies for measuring TOC involved the use of a batch process using expendable and potentially dangerous chemical reagents, relied to some degree on gravity separation, had longer periods of response, and were not as sensitive to some of the major organic compounds common to space station reclamation water.[94]

Astro was able to show that UV absorbance readings correlate reasonably well (+/- 30%) with conventional oxidation/infrared detection measurements when applied to "a variety of actual treated (recycled) water samples." However, many organic compounds, some toxic, do not absorb in the UV region. Although only 2 ppm of KHP (potassium hydrogen phthalate) is necessary to get a full scale reading, it requires over 60,000 ppm of ethanol to produce the same 100% absorbance reading. The limitations of this device are obvious.[94]



Source: "Water Monitoring Requirements, Current Requirements, and Subsystem Schematics."[35]

Figure 24. ADP EC-3 Water Quality Monitor Schematic

4.6.5 Reclamation Technologies

There are four phase change technologies and two non-phase change processes being considered for use in the WRM. The phase change technologies are distillation-type operations which separate water from waste water using evaporation, and require significantly higher energy for operation. The non-phase change technologies utilize physical and chemical processes such as particulate filtration, adsorption, ion exchange, and/or membrane technologies to separate water.[44]

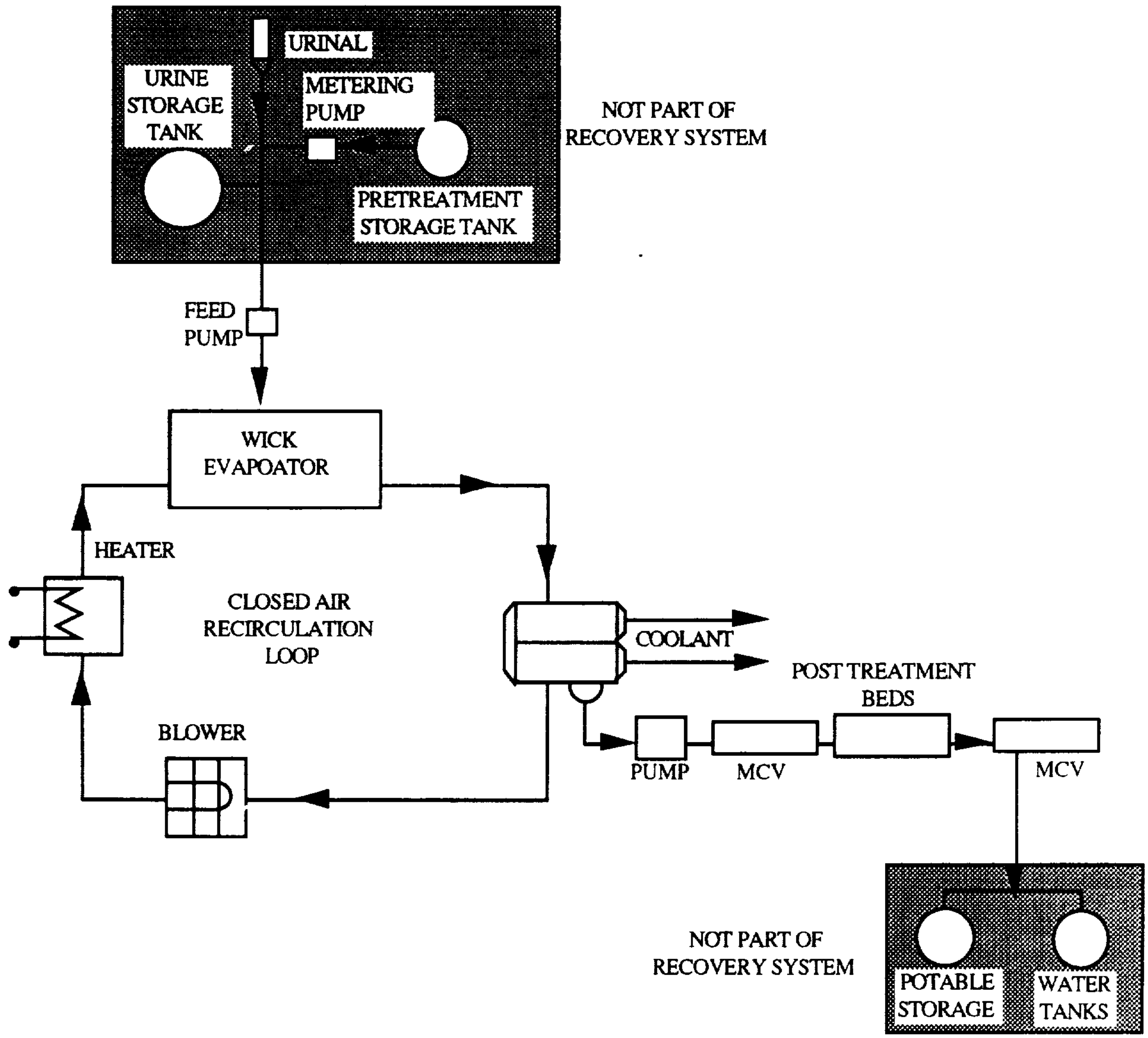
The phase change technologies include: Air Evaporation Subsystem (AES), the Thermoelectric Integrated Membrane Evaporation Subsystem (TIMES), the Vapor Compression Distillation Subsystem (VCDS), and Vapor Phase Catalytic Ammonia Removal (VPCAR). The two non-phase change technologies are Multifiltration (MF) and Reverse Osmosis (RO).

4.6.5.1 Air Evaporation Subsystem (AES)

A wick feed air evaporator is presented as an alternative to the TIMES & Vapor Compression Distillation (VCD) subsystem. A preprototype unit was produced by Airesearch Manufacturing Corp. in conjunction with Umpqua Research under MSFC contract. (See Figure 25). The system is capable of 100% water recovery from urine, wash water, RO brine, etc. It utilizes a circulating air stream, air heater, wick evaporator, and condensing heat exchanger for reclaiming process water from heavily contaminated feed streams. The AES uses a felt wick saturated with waste water as the vapor/liquid interface. Wicks load up with solids until capillary action is severely affected. The wick pads are then replaced, at an approximate rate of one wick package unit per 15 days, and spent pads with the solid contaminants are dried and placed in waste management for return to earth.[69] Water in the humidified air leaving the wick is condensed, and passed through sorbents and resins to remove volatile contaminants.[44] The system is light, rugged, and requires little power. Unfortunately wick pads must be delivered and returned from orbit indefinitely. [69]

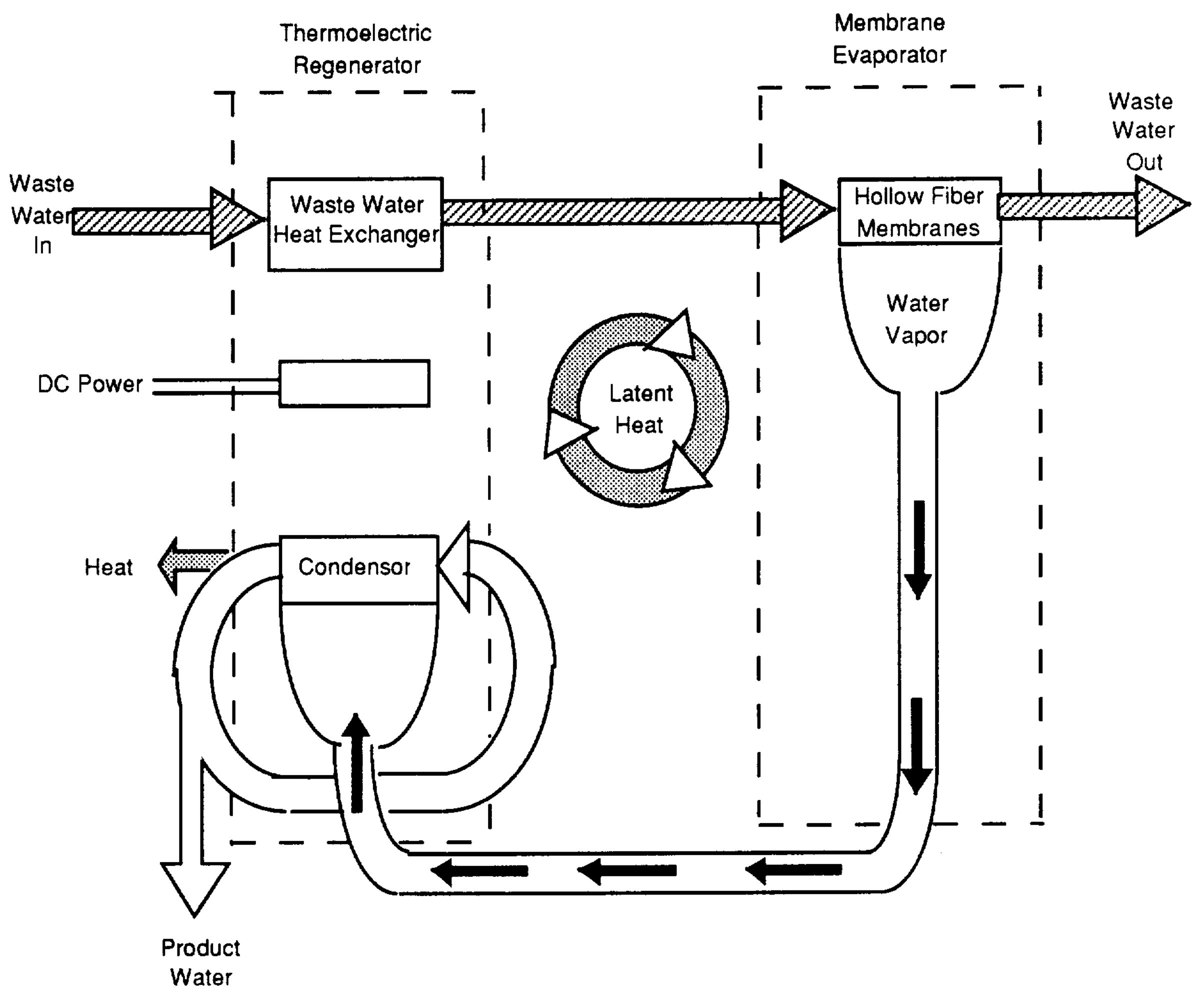
4.6.5.2 TIMES

The TIMES separates water from wastewater or urine by means of a vacuum distillation process with hollow fiber fluorocarbon based cation exchange membranes.[44,,91,103] (See Figure 26). Pretreated urine enters the recycle loop where it is heated to 135°F on the hot side of a thermoelectric heat pump. Part of the flow evaporates on the low pressure side of the hollow-fiber



Source: Morasko, C.A. Torrance, and Bagdigian. 1986. "Air Evaporation Closed Cycle Water Recovery Technology - Advanced Energy Saving Designs." SAE 860985.[69]

Figure 25. Air Evaporation System Schematic



Source: "Water Monitoring Requirements, Current Requirements, and Subsystem Schematics"[35]

Figure 26. Thermoelectric Integrated Evaporation Subsystem (TIMES) Schematic

membranes and flows to the cooler, condensing side of the thermoelectrics. Water vapor that collects on the exterior fiber surface is condensed and delivered to the post-treatment section or to the hygiene processing loop.[91] Latent heat is recirculated to the waste water. Unevaporated concentrated waste water is sent to brine storage for return to earth.[44]

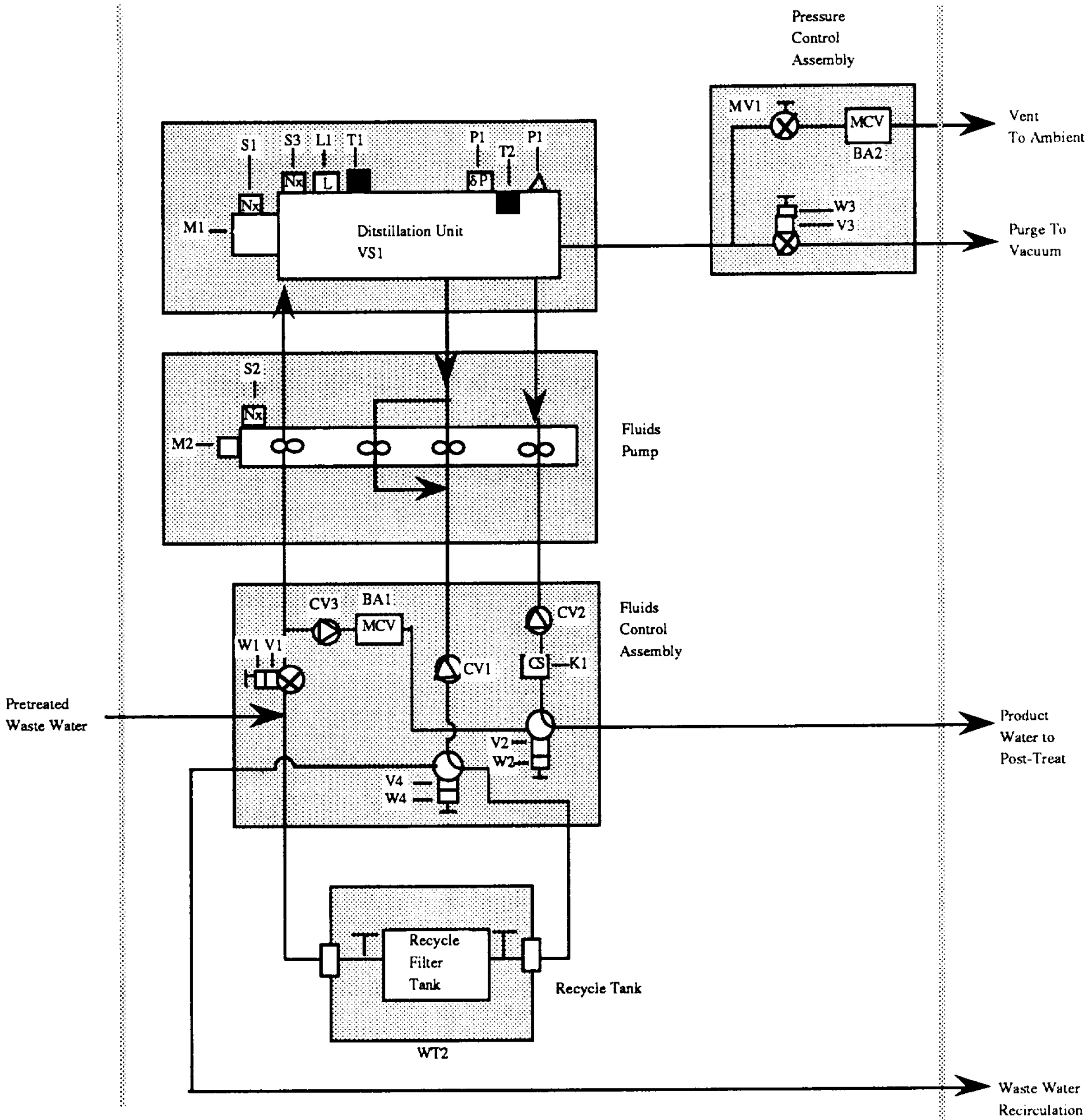
In the 1987 independent subsystem tests of the TIMES at MSFC it was found from the chemical and microbial analyses that the halogenated hydrocarbons chloroform and trichloroethane were two compounds which were found to exceed the lower limits of detection.[103] Also the raw distillate analyses for pH, ammonia, phenols, and TOC did not meet the hygiene specifications.[103] For the post treated distillate, pH, ammonia, and phenols exceeded the hygiene specifications. Since no microbial controls were incorporated in these tests, the results were not useful except in the case of the post treated distillate which showed an increase in bacteria contamination which shows that carbon contained in the post treatment bed is providing nutrients for promoting bacterial growth.[103]

In the 1987 system integration Extended Metabolic Control System Tests, the raw and post treated distillate did not meet the hygiene specifications for pH, cadmium, iron, lead, magnesium, manganese, nickel fluoride, and TOC.[103] A more complete test plan is recommended to determine raw distillate quality, and additional organic analyses will be needed to further identify organic compounds present. Additional analysis methods need to be developed to determine dissolved gas and sulfides in water.[103]

4.6.5.3 Vapor Compressor Distillation Subsystem (VCDS)

The VCDS separates water by using a rotating drum whose inside is maintained at a reduced pressure. (See Figure 27). Vapor is compressed to raise its saturation temperature and pressure, and directed to the outer wall where it condenses on a surface which is in contact with the evaporator. Latent heat is transferred via conduction through the wall of the drum to the waste water inside, and is sufficient to evaporate an equal mass of water from wastewater.[44,48] Unevaporated waste water is recirculated and stored as brine for return to Earth.[44] The VCD process has water recovery efficiencies greater than 95% from urine with 98.5% possible when processing wash water.[48]

The process control and monitoring is provided by motor-driven valves and in-line sensors. The condensate is pumped past a conductivity sensor which provides initial product water quality monitoring and controls a diverter which is activated when water quality is measured unsatisfactory. Any unsatisfactory water is reprocessed.[48]



Source: Zdankiewicz, E.D., and J. Chu. 1986. "Phase Change Water Recovery for Space Station Parametric Testing and Analysis," SAE 860986.[48]

Figure 27. Vapor Compression Distillation Subsystem Schematic

4.6.5.4 Vapor Phase Catalytic Ammonia Removal (VPCAR)

The VPCAR process was developed to produce potable water from unpretreated urine. The process is based on a catalytic chemical process whereby the impurities vaporizing with the process water are oxidized to innocuous gasses products. The VPCAR water recovery subsystem consists of the following components:

* Hollow fiber membrane evaporator
* Vapor blower/compressor for gas stream recycling
* Catalytic reactor for ammonia & hydrocarbon oxidation
* Porous tube water vapor condensor
* Catalytic N_2O decomposition Reactor

The breadboard system produces higher quality water, has lower requirements for expendables, and accumulates less sludge than the VCD or TIMES recovery systems. Even with non-optimized commercial components, the VPCAR is competitive with the TIMES & VCD in weight ,volume and power requirements. [68]

4.6.5.5 Multifiltration

In MF water flows through a series of particulate filters which remove solids, adsorption beds which contain sorbents that remove nonpolar, organic contaminants, and ion exchange resin beds which remove ionized inorganic contaminants such as salts, metal and carboxylic acids.[44] Current development is focusing on the best combinations of sorbents and resins to be used.

4.6.5.6 Reverse Osmosis

The RO system reclaims waste water by passing the water through a semipermeable membrane in a direction opposing normal osmotic flow. The dissolved and suspended material is retained in a brine solution which is held for return to Earth or reprocessed through the TIMES or VCD subsystems.

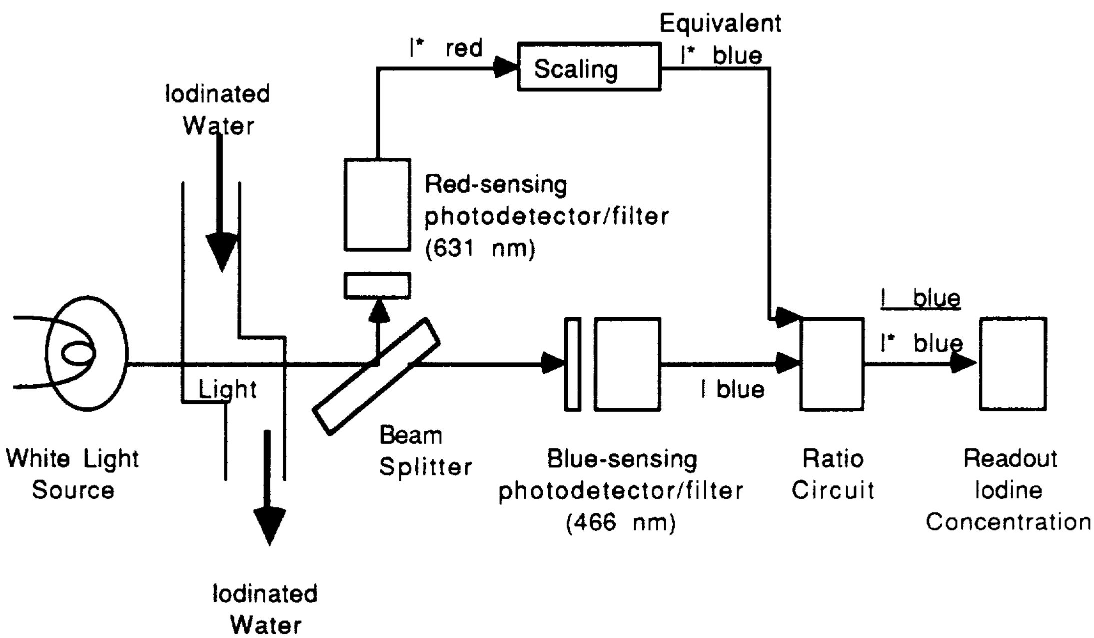
4.6.6 Subsystem Cleanliness

In a closed loop system it is essential to keep the system clean of contaminating organisms and chemicals. The use of traditional chemical biocides, disinfectants, cleansing agents and solvents may not be practical in a closed loop system because of creating waste neutralization and disposal problems, and ineffectiveness in eliminating organisms.[44] To prevent contamination laboratory-derived waste water will not be sent to the WRM subsystem. To control microbes within processing units, one approach is to incorporate a high temperature spike at the inlet using a heater/regenerative heat exchanger. Also at various waste water/process water/product water interfaces Microbial Check Valves will be used to impart a residual iodine concentration to product water at an approximate 2 ppm concentration. (See Figure 28).

To insure system cleanliness both process monitoring and water quality monitoring will be performed. Process monitoring will involve tracking a few parameters such and pH, conductivity, organic carbon, and iodine to determine if components of the process are operating properly. Water Quality verification requires testing of over 60 chemical and microbial parameters.[44] A major thrust of this development is in the microbial monitoring of water quality. Current traditional methods may take up to 48 hours to complete, as well as have problems of sample volumes, sampling equipment, storage and disposal of media, etc. For these reasons, the amount on on-board verification will need to be minimized, and methods for more rapid verification need to be developed.

4.6.7 Water Thermal Conditioning

The WRM provides water thermal conditioning services to most of the Manned Systems facilities. There are three concepts for the optimum combination of centralized and/or distributed water heating functions: centralized batch heating, distributed batch heating, and distributed on-demand heating. The first would recognize a power savings, but would require rigid scheduling of hot water usage, insulated distribution lines, and more sophisticated control. Although distributed batch heating would provide more usage flexibility, there would be maximum weight and volume penalties. The on-demand system would require significant power. These concepts are still being researched.[44]



Term Definition:

I = light intensity signal attenuated by Iodine

I* = light intensity signal unattenuated by Iodine

C = concentration of attenuating species (Iodine)

Source: "Water Monitoring Requirements, Current Requirements, and Subsystem Schematics"[35]

Figure 28. Iodine Monitor Schematic

4.7 ECLSS Application Software

4.7.1 Command and Control Architecture

The onboard command and control architecture implemented by ECLSS applications is hierarchical consisting of four levels (or "Tiers") of operational management. These range from Tier I, the highest and most generalized level of operations management, to the very task specific Tier IV operations management [5,6]

4.7.1.1 Tier I Software (Top Level)

Tier I provides for the integration of systems, elements, and payloads. It operates at station level and consists onboard of the crew and Operations Management Application (OMA) and on ground of the Operations Management Ground Applications (OMGA), station operators and payload operators on the ground, the Space Station Control Center, and the Payload Operations Integration Center. (See Figure 29) [5,6]

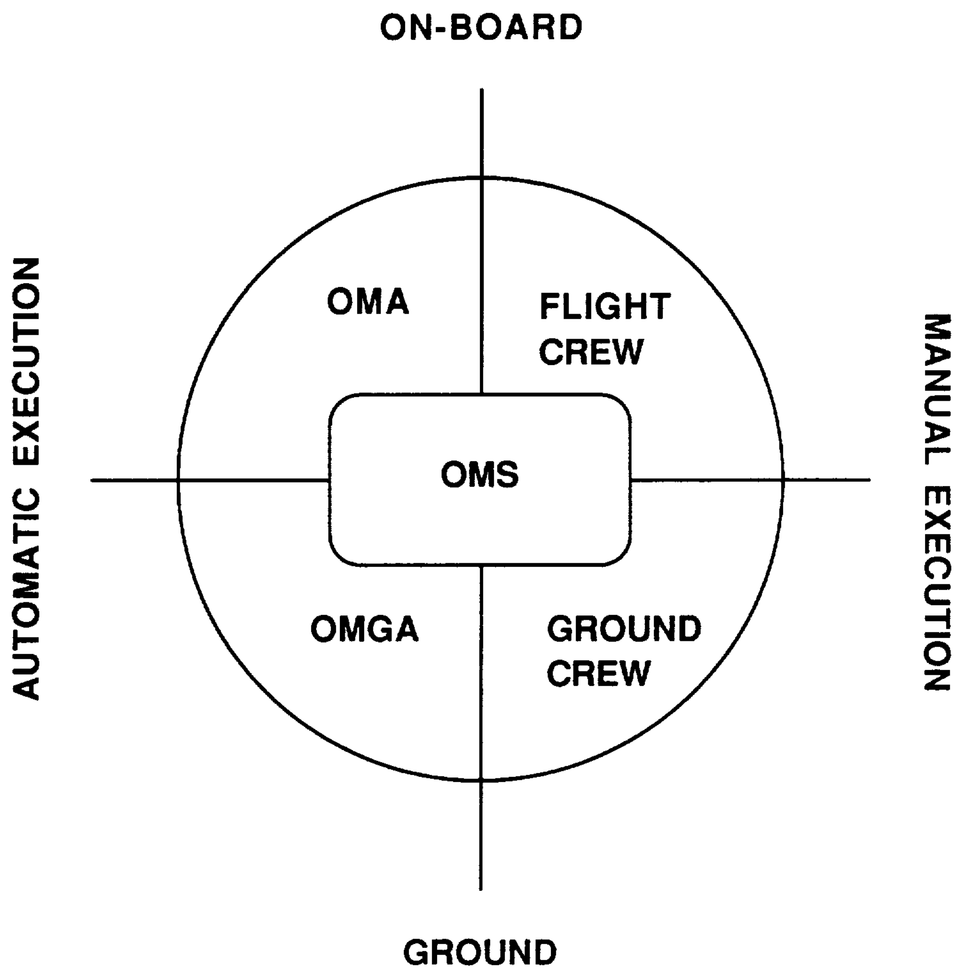
4.7.1.2 Tier II Software (System or Element Manager)

The ECLSS Manager is located at Tier II. Its primary responsibility is to coordinate the activities of each of the six subsystems of ECLSS across all of the pressurized modules. This control includes operation within assigned operational envelopes, monitoring the system health and status, and performing Failure Detection, Isolation, and Recovery (FDIR). It is this coordination that accomplishes the station-wide functioning ECLSS.[5,6]

4.7.1.3 Tier III Software (Elemental Level)

The third tier is located at the element level. The element ECLSS manager coordinates and controls ECLSS functions across rack boundaries. They are designed to be autonomous within that element, but are capable of working with the Station level ECLSS managers when necessary. The responsibilities of the element ECLSS managers shall include:[5,6]

A. Command and control, including data handling and command checking and verification.



The automated portion consists of:

- Operations Management Application (OMA) on-board flight software
- Operations Management Ground Application (OMGA) ground software

The manual portion consists of:

- On-Board flight crew
- Ground crew and flight controllers

Source: NASA. 1989, "Architectural Control Document Data Management System Part 2: Operations Management System," Preliminary Draft Copy, NASA, December 15, 1989.[7]

Figure 29. Operations Management System (OMS) Functional Design

A. Command and control, including data handling and command checking and verification.

B. Provision for appropriate manual overrides, dynamic limit setting, and process activation and inhibition.

C. Fault detection, isolation to the ORU level, and recovery including corrective action response and emergency reconfiguration control.

D. Detection of all critical system failures.

E. Performance and trend data analysis.

F. Provision of static display data for system monitoring, command and control.

G. Updating of dynamic display data.

H. Monitoring and reporting of the status and health of the ECLSS subsystems within the element to Tier II.

4.7.1.4 Tier IV Software (Rack Level)

The fourth tier is located at the rack level. The rack level ECLSS Managers monitor and control the ECLSS functions within each rack of the element. This layer interfaces with Tier III to complete the ECLSS architectural structure.

4.7.2 Data Management System (DMS)

Provides:

1. An application processing, process control and data handling environment for onboard systems, elements, and payloads.
2. Software that permits the integration of the operations environment.

Hardware Resources:

1. Application and network communication processors
2. Mass storage units
3. Electronic work station components for control and monitoring.
4. Data acquisition and distribution components.

Software Resources:

1. Operating system and ADA run time environment.
2. Communication services.
3. Data Storage and retrieval services.
4. Data acquisition and distribution services.
5. Time distribution services.
6. Crew interface services.

4.8 ECLSS Subsystem Integration

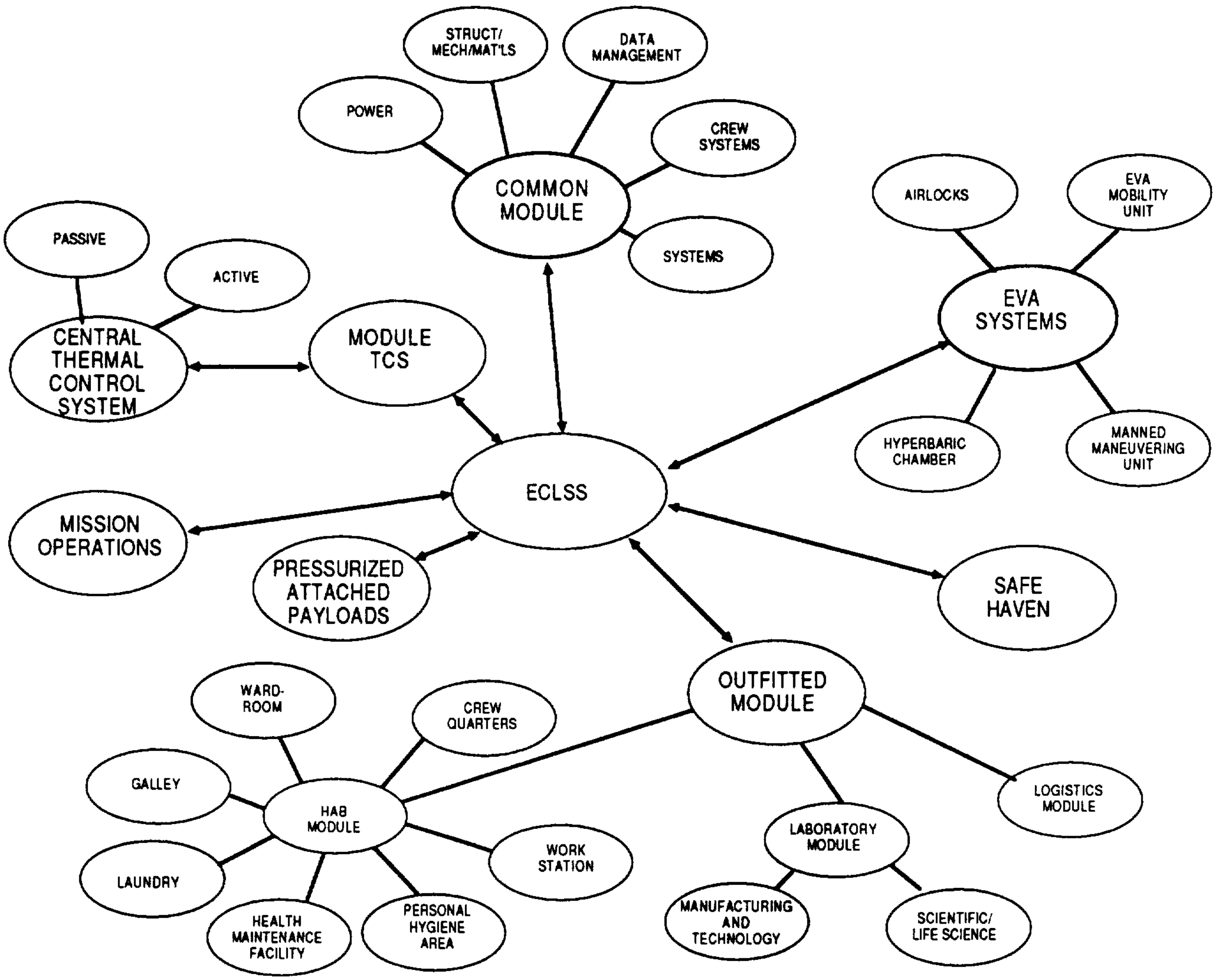
The configuration of the ECLSS is a closed loop which will result in lower orbit weight and resupply penalties.[70] (See Figure 2). With the ECLSS configuration being a "racetrack" design, the equipment is physically distributed to be able to operate while sustaining a loss of a module, thus fulfilling the "safe haven" requirements. The design functionally centralizes equipment where possible, particularly where systems can be extended through the docking ports, and there are no fluids transport or contamination concerns.[88] The potable and hygiene water subsystems are centrally located in the two HAB modules and provide services to multiple Space Station Freedom elements.[107] Urine and fecal collection and processing will be located in the HAB and LAB modules.[88] The AR is centrally located and is connected to other Space Station Freedom elements through the intermodule air distribution system.[88] Hydrogen gas and carbon dioxide are not distributed between modules due to safety considerations. Oxygen and nitrogen are centrally distributed. All other ECLSS functions provide their services only in the Space Station Freedom element where the subsystem is located.

"Safe Haven " is a big consideration in the location and distribution of subsystems. Subsystems that are functionally distributed, being only in the Space Station Freedom element where the subsystem is located, are redundant within that element. Under safe haven systems must be able to support emergency operating conditions for 45 days.[88] Safe Haven conditions are met either by redundancy of life critical functions, or by use of alternate technology equipment. Safe Haven is instigated after two non-repairable failures of a safety-critical subsystem, or after the loss of any single module. Therefore, safety-critical subsystems must be located in two modules.[107,5] The two U.S. modules are the designated safe haven elements, so each element must be able to support the entire eight person crew under emergency operating conditions.[88,107,5] The crew safety critical subsystems are CO_2 removal, CO_2 reduction, O_2 generation, and potable water reclamation.

Stand alone and integrated system testing has been performed. Three integrated tests during the 1988 Phase II program were successfully performed. The 1989 Phase III program is aimed at enhancing the water reclamation system. Major issues of the Phase III tests include maintaining microbial and chemical cleanliness during extended duration simulations.

4.9 ECLSS Subsystem Interfaces With Other Systems

The ECLSS interfaces with many other modules and systems, the primary ones being with the laboratory modules, manned system habitability, Extracvehicular Activity (EVA), and pressurized module attached payloads. ECLSS design has been influenced by these interfaces.[70](See Figure 30).



Source: Ray, C.D., and W.R. Humphries. 1986. "Status of the Space Station Environmental Control and Life Support System Design Concept," SAE 860943, 16th Intersociety Conference on Environmental Systems, July 14, 1986.[20]

Figure 30. ECLSS Interfaces

5.0 DETAIL OF POTABLE WATER SYSTEM

The following potable water treatment subsystem description is as defined in Appendix A document #114 "Phase III CMIF Recovery System/Facility Design Requirements" dated November, 1988; prepared by R. Bagdigian, and approved by W.R.Humphries and J.L. Vaniman. This baseline design configuration includes those subsystem technologies deemed most likely to produce product water meeting NASA Space Station Freedom water quality requirements at this time. For the most part the technologies chosen are those which have resulted from a relatively large amount of development work. These subsystems currently exist as advanced prototype hardware. The potable water system is still under development, however, and the reader should keep in mind that alternative technologies exist for many of these processes and development work currently under way may produce alternative subsystem hardware with superior performance characteristics.

The Potable Water Multifiltration Subsystem (PWMFS) produces potable-grade water from a mixture of humidity condensate, carbon dioxide removal by-product water, and carbon dioxide reduction water. (See Figure 31). In the first half of the process, known as the sterilizer assembly, the waste water enters the PWMFS through a shutoff valve to a positive displacement gear pump. Positive displacement gear pumps are a form of metering pump which insures a constant volume flow rate at a particular pump speed setting. The pump feeds the water through a regenerative heat exchanger, heater, and heater reservoir which sterilize the water by heating the water to 250°C for 20 minutes. A back pressure regulator maintains the pressure between 37.5 and 37.0 psig to prevent steam formation and assure the desired biocidal action. There are four temperature sensors, one pressure transducer, and a high and low level sensor in the feed tank.[14]

In the second half of the process the water flows through a 2 micron prefilter for particulate removal, and a series of six identical sorption beds (Unibeds) which are packed with sorbents and resins that remove dissolved contaminants. Specific sorbent types and function, in order of flow are as follows:[52,14]

Sorption Media	Function	Amount
(1) MCV-L	Polyvinyl pyrolidone (PVP) iodine	96 g.
(2) IRN-77	Strong acid cation resin	90 g.
(3) IRA -68	(Undefined ?)	60 g.
(4) 580-26	(Undefined ?)	535g.
(5) XE-347	(Undefined ?)	70 g.
(6) APA	Activated carbon	64 g.
(7) XE-340	(Undefined ?)	70 g.
(8) XAD-4	Polymeric absorbant	60 g.
(9) IRN-150	Strong acid/base mixed resin	90 g.
(10) MCV-H	PVP iodine ?	97 g.
(11) IRN-77	Strong Acid cation resin	90 g.

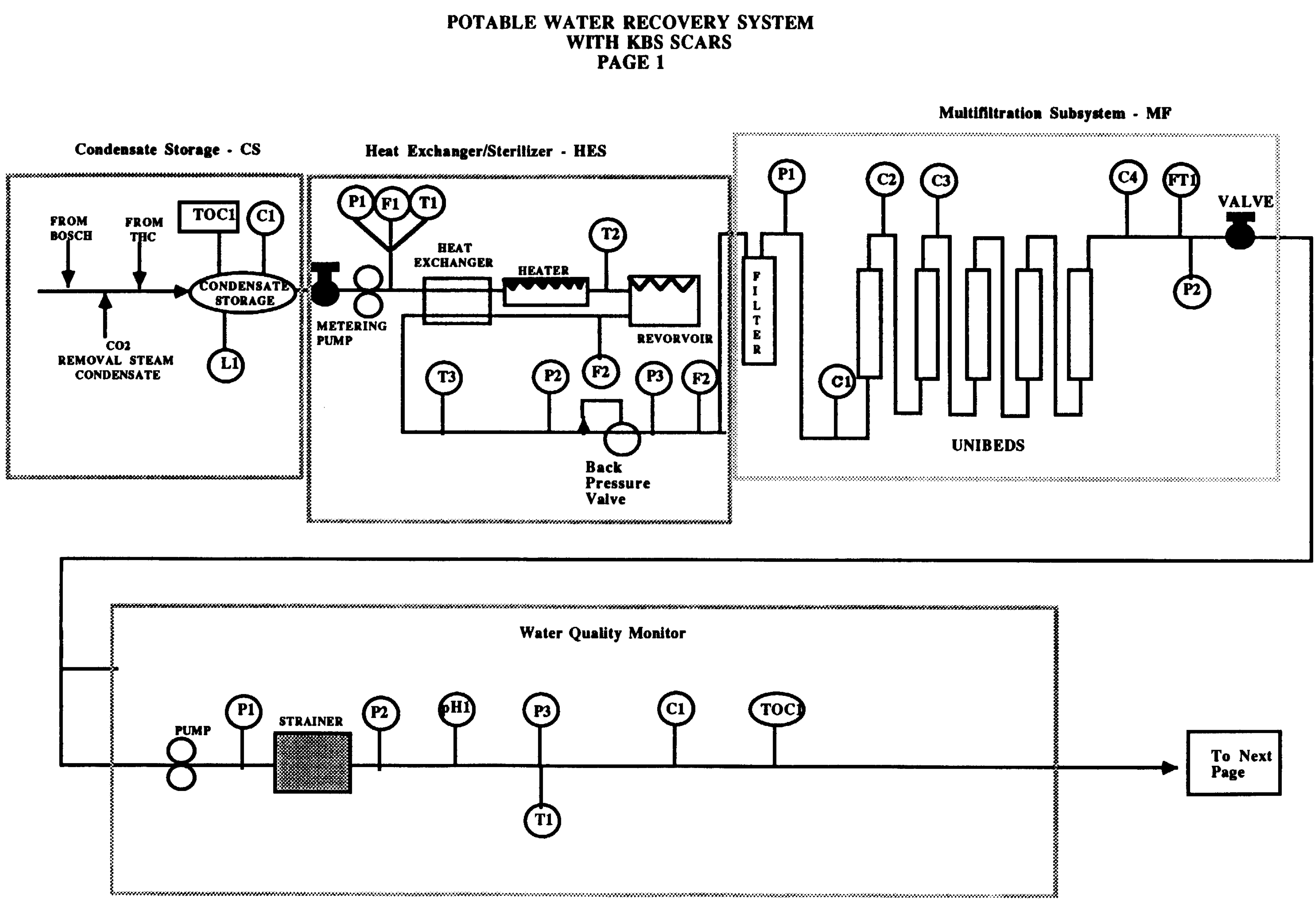


Figure 31. Potable Water Multifiltration Subsystem (PWMFS) Schematic

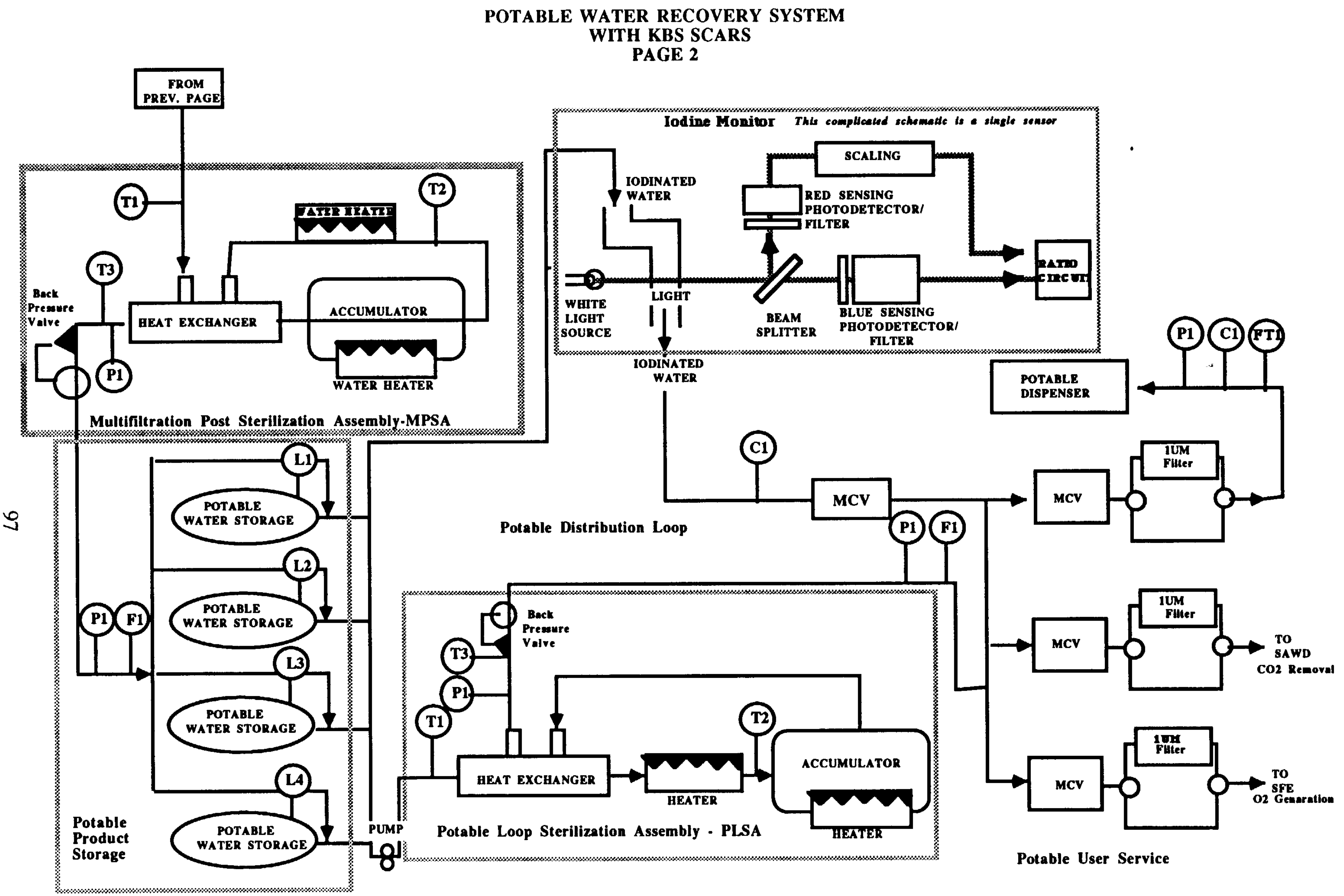


Figure 31. Continued

There are pressure sensors before and after the prefilter, conductivity sensors before the first, second, and third Unibed, and after the sixth Unibed; sample ports after the prefilter and the first 5 Unibeds; and a flow totalyzer after the last Unibed. Effluent exits the subsystem through a manual shut off valve and is delivered to a product tank. The product tank also has high and low level sensors.[14] When the first Unibed becomes saturated it is removed from the system and the valves are reconfigured to move the remaining beds up in position with a fresh bed placed in the last position..[52] There are manual on/off switches on the pump and on the resistant heaters in the heater and heat reservoir. There is also automatic control of the pump on/off control which is controlled by float sensors in the feed and product tanks. The pump is turned on when the high level sensor in the feed tank is activated, and is turned off when the low level sensor in the feed tank is deactivated or the high level sensor in the product tank is activated.[14] The third temperature sensor on the Heat reservoir controls the flow to the heater by sending signals to a temperature controller at the control monitor panel. If maximum allowable temperatures of 255^{o}F are exceeded, and alarm signal sounds, but no automatic action is taken.[14]

The conductivity sensors, which measure water quality, control the pump by sending signals to two conductivity controllers at the control monitor panel. The pump is automatically stopped when the first Unibed is shown by the conductivity sensors to have exceeded its conductivity limits. The process is also automatically shutdown when the outlet conductivity exceeds 10 micromohs/cm.[14] Manual shutdown of the entire system is controlled by a power switch on the control panel, which overrides all other controls.[14]

APPENDICES

APPENDIX A - Annotated Bibliography

1.) UAH Preliminary Research Task (Flow Diagram). ECLSS Advanced Automation Project. NASA/MSFC.

2.) Year/(FY 89) Task Schedule (Chart) ECLSS Advanced Automation Project. NASA/MSFC.

3.) Space Station Freedom Advanced Development Project Plan. The Environmental Control and Life Support System Advanced Automation Project. Dewberry, Brandon S. NASA/MSFC.

4.) A Review of Space Station Freedom Program Capabilities for the Development and Application of Advanced Automation.
Bayer, Steven E. et al,. December 1988.

Page ix presents the idea of the Integrated Communications Officer [INCO] Expert System Project [IESP]. (See also page 44.) This may provide a good idea of the layering of the software system. It should also give us some idea of the kinds of considerations that are relevant to the Space Station project. Page 13 describes the Operations Management Application [OMA]. HABOMA is the Habitat OMA. Page 15 describes the Procedure Interpreter. This one sounds like a winner for a KBS. It is designed to present procedures in context, that otherwise would be hardcopied into the Flight Data Kit. It seems as though this Interpreter would leverage the ideas of Joshua and Concordia. Page 47 begins the discussion of the Software Support Environment. This is a good background for the Distribution charts. Page 57 begins a discussion of the Evolution of Advanced Automation. This is a good background for understanding the ideas of hooks and scars. Appendix A, beginning on page 75, gives a taxonomic presentation of AA efforts. We should have a section of our report that fits our work into the taxonomy.

5.) Environmental Control and Life Support System Architectural Control Document NASA Marshall Space Flight Center, February 15, 1989.

Page 3-3 and 4 contains a brief definition of of the WRM. This is the subsystem in which potable water is contained. See also 3-8 and 3-9. ECLSS applications software begins on 3-10. Note that the idea of "Tiers" supports the idea that the context diagrams are hierarchical. Page 3-16 through 3-17 present some shalls for the WRM. It would be good to compare these to NASA 3000 extracts. Table 3-1 (page 3-34) provides some of the specifications for what WRM should do. Need definitions of lbm, person-day, HMF, and PEP. Note that tables 3-4 and 3-4a present the intriguing issue of what to do about experimental animals. Figure 3-1, page3-46, presents a diagram that on the left hand side seems to indicate the layout of parts for potable water and WRM. See Figure 3-6, page 3-51, for specific schematic of WRM.

6.) Architectural Control Document Data Management System Part 1: Integrated Avionics Preliminary Draft Copy. NASA, December 15, 1989.

Note the specification of DMS services on page 3-3 and the material on pages 3-17 and 3-18 for ECLSS (where avionics appears).

7.) Architectural Control Document Data Management System Part 2: Operations Management System Preliminary Draft Copy. NASA, December 15, 1989.

If we understand this, correctly ECLSS itself should be considered a system manager. See pages 6-8. Note two types of system manager page 11-12. The OMA and OMGA are described and this can give a better idea of the overall OMS. OMA ECLSS characterized again on page 15. The Table 3-1 of Tier II managers is important. The column for DMS and ECLSS indicate what sorts of things might be provided on which a KBS might operate and what sorts of things ECLSS should be able to do. Much of the areas listed are TBD. Table 3-1 is very important.

8.) Architectural Control Document Data Management System Part 3: Data Management System. Preliminary Draft Copy. NASA Space Station Freedom Program, Office Reston, Virginia, December 15, 1989.

Hooks and scars defined! A hook is a design accommodation to facilitate the addition or update of computer software at some point after the start of station operating life. A scar is a hardware hook. This document is primarily about hardware. Software begins on page 3-32. The Management section that begins on page 3-42 indicates the kinds of things that are offered in general to a manager. The services seem designed to make any particular software item an imbedded item. This is a reasonable conclusion since Ada is supposed to be for imbedded systems.

9.) Space Station Advanced Automation Study Final Report. Strategic Plans and Programs Division, Office of Space Station, NASA Headquarters,
May, 1988.

This is a most helpful document. Sections 2 and 3 seem to be the most important. Page 3 gives the clearest account of the specifics that we must to some degree satisfy. Note for example that page 23 begins a discussion of what was NOT selected for baseline.

10.) Ada and Expert Systems. Allen, Bradley P, Inference Corporation.

Seems to say what INFERENCE wants to do. They made the split between imbedded real-time systems and decision support systems.

Defines two types of ADA expert systems as embedded real-time systems and decision support support systems. Lists problems in ADA expert system shells:

a) size of the executable code
b) run-time memory utilization
c) unpredictable response times

Describes transitional development from C and ADA tool to a stand alone ADA development tool.

11.) Art/Ada Design Project - Phase I Project Plan. Status Report. March 1988 - October 1988 Allen, Bradley P. Inference Corporation October 24, 1988.

Most of the information addresses specifically the development of ART using ADA. However some general considerations for expert system development are also listed.

12.) ART/Ada Design Project - Phase I Task 1 Report: Overall Design. Status Report. March 1988 - October 1988 Allen, Bradley P. Inference Corporation October 24, 1988.

These articles document the progress made in the ART/ADA development. This tool is a more robust development tool than CLIPS, But for our purposes CLIPS should provide an adequate amount of flexibility.

13.) ART/Ada Design Project - Phase I Task 3 Report: Test Plan. Status Report. March 1988 - October 1988 Allen, Bradley P. Inference Corporation October 24, 1988.

See Article 12.

14.) Test Plan for Potable Water Multifiltration Subsystem Checkout and Performance Verification. McGriff, C. F. and Carter, D. L.December 19, 1989.

This test plan gives an excellent description of the PWMFS hardware and operation. The PWMFS will produce potable grade water from humidity condensate and CO2 reduction water. This subsystem consists of a heat exchanger - sterilizer fed by a gear pump , a 2 micron prefilter and five UNIBED mixed exchange resin filters. The subsystem is controlled via 4 thermocouples, 3 pressure transducers, 2 level sensors, and a total flow meter. Diagrams and schematics are included. Subsystem designed by Umpqua Research Company for Boeing Aerospace.

15.) AI Applications for the Space Station. Culbert, Chris et al. NASA/Johnson Space Center, 1988.

General background.

16.) ECLSS Advance Automation Project.

General background.
17.) TES - A Modular Systems Approach to Expert System Development for Real-Time Space Applications. Cacace, Ralph and England, Brenda. United Technologies Corporation.

General background. Illustrates the application of several common techniques.

18.) Simulation and Control of a Space Station Air Revitalization System. SAE Technical Paper Series. 871425. Yandsy, James L. and Rowell, Lawrence F. 17th Intersociety Conference on Environmental Systems. July 13,.1987.

Describes the G189A computer simulation tool for simulation and control of a space station air revitalization system. One of a variety of software tools developed by Langley for design ,development, test, and engineering (DDT&E).Gives a good text and graphics description of an early proposed Space Station ARS. One typical group of technologies and plumbing configuration was modeled as a baseline for later comparison with other technologies.

This document gives a good general overview of candidate technologies and basic concepts for an ARS. Some helpful baseline data such as:

* Atmosphere leak rates
* Atmosphere replenishment tank volumes
* O_2 consumption &
* CO_2 production - relative to crew size

19.) Environmental Control and Life Support Testing at the Marshall Space Flight Center. SAE Technical Paper Series. 871453. Schunk, Richard G. and Humphries, William R. 17th Intersociety Conference on Environmental Systems. July 13, 1987.

20.) Status of the Space Station Environmental Control and Life Support System Design Concept. SAE Technical Paper Series. 860943. Ray, C. D. and Humphries, W R. 16th Intersociety Conference on Environmental Systems. July 14, 1986.

Good review of ECLSS. Page 5 indicates in a broad way the services that the ECLSS modules provide. Not that on page 8 it is clearly indicated that potable water comes from condensate.
21.) Artificial Intelligence Research and Applications at the NASA Johnson Space Center. Healey, Kathleen The AI Magazine, August, 1986.

A general discussion of a variety of issues. Page 109 the ESRA and CCM are of interest.

22.) Test Plan for Potable Water Multifiltration Subsystem (PWMFS) Checkout and Performance Verification. McGriff, C. F. and Carter, D. L.,Dec 19, 1988.)

Duplicate of document 14

23.) A Method for Evaluating Candidate. Slagel, James and Wick, Michael, AI Magazine, winter 1988.

The SLAGEL-WICK model ought to be fully integrated into the general NASA ideas about candidate systems. We are working on this and generating a hyperCard template.

24.) Space Station Program Interface Requirements Document (Software). IBM Systems Integration Division, November 15, 1988.

Technical specs on software. There is a lot of detail in the sense of functions and facilities that should eventually be available.
25.) Space Station Program Software Requirements Specification for the Data Management System Standard Services. IBM Systems Integration Division, November 15, 1988.

Technical specs on software. There is a lot of detail in the sense of functions and facilities that should eventually be available. Together documents 24 and 25 give a good account of the services offered by the distributed database. They in some ways provide a model for thinking about a distributed KBS.

26.) Artificial Intelligence, Expert Systems and Technology Working Group, Status, Plans, Schedules. Webster, Larry D., AIESTWG, February 22, 1989.

Mainly a chat about a meeting but... The slides present a good deal of current information. For example there is a statement of goals. This is good since it lays out some general constraints. There are also lists of members and wish lists! Part of what we are doing is responding to some section of the wish list.

27.) Space Station Reference Growth Configuration Data Book R&D Emphasis. Early Concepts Data Drop Review Draft. McDonnell Douglas, February, 1989.

Purpose of this data book is to define the requirements for Space Station growth, identify growth concepts for Space Station subsystems, and to present configurations for orderly growth during Space Station evolution. The data book shall be used to support baselining of the reference growth configuration by the Space Station Program Levels I and II and to provide data to the Work Packages to insure proper implementation of hardware scars and software hooks which will allow a smooth transition from the Phase 1 configuration through a series of growth phases to insure proper implementation of scars and hooks.

Phase I Growth Configurations: Space station growth is derived from mission accommodation analyses performed for two utilization emphases 1)microgravity research utilization, and 2) life science research utilization. The accommodation analyses were based on two transportation models: 1) moderate transportation support model, and 2) aggressive transportation support model. Four mission accommodation scenarios were evaluated. Evolution growth blocks are used to show incremental growth steps for space station systems such that a balance of resources is provided so that excesses or deficits are avoided in resources such as power, crew and pressurized volume. Components are added to the Space Station with reference to operating year and transportation support. Growth elements include: Solar Dynamic Modular pair, Transverse Boom Extensions, Orbital Maneuvering Vehicle, Resource Nodes, Hab Modules, Crew Emergency Return Vehicle, Keel Booms, Customer Servicing Facility, Docking Masts, Lg Pocket Lab, Lab Module, Space Transfer Vehicle Hanger, Back Porch, and Sm Pocket Lab.

Space Station Subsystem growth requirements:
Describes configuration of Module growth patterns. No specifics were given on Mechanical Systems, Utility Distributions, the Communications Tracking System, Airlock, Operations Management, Mobile Servicing Center, or attached Payload Accommodation, and are to be supplied later. Under Customer Servicing the transverse boom will be scarred to accommodate full development of the Space Station module patterning while maintaining National Space Transportation System (NSTS) cargo transfer capabilities.

Appendices:

- A: Table 4 shows a Resource Allocation to R&D
- B: Shows Resource Allocation functions and equipment weights going up and returning after completion.
- C: Shows distribution of Space Station Resources and resource balance for the microgravity research utilization emphasis, moderate and aggressive transportation growth scenario; and life sciences utilization emphasis, aggressive transportation.
- D: Contains time-phased growth block analysis of the mission accommodation scenarios.

28.) Rack and Subsystem Level Schematics. Carter, Charve. Boeing Aerospace. Along with ECLSS Subsystem Groups and General Regenerative ECLSS Flow Diagram.

This paper is a good general overview of ECLSS subsystems.The "General Flow Diagram" (same as in Doc. #1) is helpful and easy to read, everyone should look at this.Individual module schematics are quite complex and copy quality makes them nearly cryptic (will continue in depth analysis per weekly status.)

SIX ECLSS SUBSYSTEMS

1. THC- temperature and humidity control
    - A. temp & humidity control
    - B. Avionics cooling
    - C. Process air
    - D. Thermally conditioned storage (TCS)

2.ACS - atmosphere control and supply
   A. pressure control
   B. Composition control& monitoring
   C. gas storage
   D. Vent & relief
3. AR - atmosphere revitalization
   A. CO2 removal
   B. CO2 reduction
   C. O2 generation
   D. trace contaminant control
   E. trace contaminant monitor
4. WRM - water recovery and management
   A. potable recovery
   B. hygiene recovery
   C. urine water recovery
   D. water quality monitor
5.WM - waste management
   A. fecal processing and storage
   B. return waste storage
6.FDS - fire detection and suppression
   A. fire detection
   B. suppressant storage (CO2)
   C. suppressant distribution

The first of three Basic Schematics show the ECLSS subsystem groups with it's six groups contributing to the space station: Temperature and Humidity control (THC), Atmospheric control and supply (ACS), Atmospheric Revitalization (AR), Water Recovery and Management (WRM), Waste Management (WM), and Fire Detection and Suppression (FDS). The second schematic is the general regenerative ECLSS Flow Diagram which shows how some of these subsystems interact to recover potable water from Urine recovery, waste water and product water recovery, and humidity condensate and process air. The third schematic shows the ECLSS schematic in more detail including where subsystems will be used in the different Nodes and Modules. ACS, THC, and FDS are components of all modules, and are the only subsystems in the Nodes, Hyperbaric airlock, and airlock. The logistics module has in addition to those three, Thermal condensate storage. The Lab Module and the HAB Module have all six subsystems, and AV air, with the HAB module also having Thermal condensate storage. There are no indications on any of these three schematics as to computer driven processes.

Rack and subsystem level schematics are shown in the remaining schematics. Many of these have been reduced so much that they are illegible to someone who does not know the engineering symbols used by the preparer. Schematics are included for Hygiene Water Processors, Urine Processor/refrig. Film Locker Rack, Potable Water Processor, Atmospheric Revitalization, THC/TCS/Avionics Air, THC,WRM, Oxygen Distribution, Nitrogen Distribution, Vent relief assembly and pressure equalization, avionics air/log, HAB lab THC mechanical, HAB lab avionics cooling, and cabin air/avionics cooking mechanical.

29.) Distribution Flow Charts.

These are being set into hypercard. The stack will allow you to follow the path through the distribution. The materials in 31, 32, 33, and 34 hit similar topics. See the overview stack.

30.) ART/Ada Design Project - Phase 1 Task 2 Report: Detailed Design. Status Report. March, 1988 - October, 1988. Allen, Bradley P. Inference Corporation, October 24, 1988.

More Art/ADA see articles 11 and 12.

31.) ECLSS Advanced Automation Preliminary Research Task. (overheads). NASA - MSFC.

32.) WPO1 ECLSS Software Architecture. Berner, S. A., Boeing. April 26, 1989.

33.) Incorporation of Software Automation in ECLSS. PDT Briefing, April 10, 1989.

There does not seem to be anything specifically relating to what we are doing.

34.) WP-1 ECLSS Data Management System. McCall, B. Boeing Aerospace. April 26, 1989.

35.) Water Monitoring Requirements, Current Requirements, and Subsystem Schematics

36.) Regenerative Life Support System Research and Concepts Progress Report During the Period of April 1988 - December 1988. By The Regenerative Concepts Team, Texas A&M University. Available in document library, (RI m-56) also from M. Kilgore.

37.) Regenerative Life Support System Research and Concepts Progress Report During the Period of September 1987 - March 1988 By The Regenerative Concepts Team, Texas A&M University. Available in document library, (RI m-56) also from M. Kilgore.

38.) Space Station Man-systems Integration Standards. NASA-STD-3000 Volume IV Baseline December 18, 1986.

This document lists, in a very general manner how NASA would like the differing systems within Space Station to operate which doesn't help us much. However, this report does include one very interesting table of information. Figure 7.2.2.3.2.1-1 (page 7-3) lists the Potable Water Quality Limits.

39.) Space Station Environmental Control and Life Support Systems, Test Bed Program - An Overview Behrend, Albert F. Jr.

NASA has established generic test bed capabilities in which ECLSS has been implemented. To demonstrate that regenerative processes is the best solution to consumables. Reviews the history of ECLSS testing to this point. The ECLSS Test Bed Facility had three elements: 1) ECLSS Development Laboratory, 2) ECLSS Component Endurance Laboratory, and 3) Integrated ECLSS Test Bed facility. The primary objective was to conduct a 90-day manned test by May 1988. Subsystems selected for test bed incorporation are oxygen generation using static feed solid polymer electrolyte water electrolysis, Carbon dioxide removal using electrochemical depolarized carbon dioxide concentrator, carbon dioxide reduction using Sabatier, and Potable/Hygiene water recovery using Vapor Compressor Distillation. Alternative tests will also be done, using in respective order: static feed water vapor electrolysis, solid amine water desorption, Bosch, and hyperfiltration/reverse osmosis. Maturity of new technologies will be demonstrated and, as such, will minimize program risk and permit intelligent programmatic decisions to be made.

40.) Feasibility of Expert Systems to enhance Space Station Subsystem Controllers Malin, Jane T. and Nick Lance, Jr., Space Station Automation, Vol. 580, 1985

This 1985 report discusses the need and practicality of applying expert system technology to a wide variety of controller and diagnostic systems. Table 1 (page 29) lists the controller functions. A CO2 removal system was used in the development of a fault management expert system. The systems development, using KEE, is described. This might be helpful when it is time for our prototype development.

41.) Study and Approach on Artificial Intelligence Testing, Progress Report Prepared for Boeing Aerospace Company by Vanderbilt University December, 1988

42.) ECLSS Integration Analysis - Requirements Analysis of a Knowledge Based System (KBS) for the Space Station Environmental Control and Life Support System. MDC W5184. May 9, 1985

Lists two types of ECLSS data:

1) data normally processed by the Space Station DMS
2) internal process data.

The functions provided by the DMS are:

* Process status and performance monitoring
* Process command and control
* Historical data storage/recall
* Fault detection, isolation, and response (FDIR)
* Redundancy Management

Describes three tier ECLSS design. The STATION LEVEL ECLSS will interface with the OMS which will more than likely be originally located on the ground. On page 2-2 a list of eleven functional requirements of the OMS and a system schematic. The primary objectives of an ECLSS KBS is to reduce and supplement manpower and to reduce ECLSS hardware downtime. The typical tasks and areas for trend analyses are listed on page 3-1. The report contains a brief section on the AR and WRM subsystems that might be worth everyone reading. In this section some generalized applications are listed and measurement lists included.

43.) Environmental Control Life Support for the Space Station 860944, Miller, Craig and Kovach, Licia. Life Systems, Inc.

Summaries of ECLSS trade studies are presented. The analysis included the identification of time-critical functions, redundancy (backup) management, definition of common subsystem interfaces and quantification of technology options for the process equipment. Each technology was characterized by its physical characteristics of weight, power, volume, heat rejection, etc.

44.) Status of the Space Station Water Reclamation and Management Subsystem Design Concept. SAE 871510. Bagdigian, R. and Mortazavi. Life Support Branch, Marshall Space Flight Center, Huntsville, AL. 1987.

The current status of the Space Station Freedom water reclamation and management (WRM) subsystem is outlined. The requirements and general architecture of the WRM are described. The main function of the WRM subsystem is to provide a safe, reliable supply of water to meet Space Station Freedom needs, while minimizing water-related resource requirements. It describes the two grades of water: Potable (crew-ingestable) and hygiene (non-ingestable) and the current technologies being developed to produce these waters. Table 1 shows Functional and Performance Requirements, Table 3 lists the some 60 Water Quality Requirements. The WRM subsystem

includes processors to reclaim or recycle water from various wastewater sources, as well as hardware to monitor water quality, provide water thermal conditioning, and store and distribute water throughout the Space Station Freedom. Some technologies described are the Air Evaporation Subsystem (AES), the Thermoelectric Integrated Membrane Evaporation Subsystem (TIMES), the Vapor Compression Distillation Subsystem (VCDS), and the Multifiltration and Reverse Osmosis subsystems. Chemical and microbial control is discussed. Urine pretreatment and thermal water conditioning are briefly discussed.

45.) Environmental Control and Life Support Systems Technology Options for Space Station Applications. SAE 851376. Hall, John and Ferebee, Melvin, NASA Langley Research Center and Sage, Karen, Kentron International, Inc. Hampton, VA. July, 1985.

46.) Space Station Environmental Control/Life Support System Engineering. SAE 851375. Miller, C. and Heppner, D. Life Systems, Inc. July, 1985.

47.) Evaluation of Space Station Thermal Control Techniques. 860998. Hall, J. B. NASA Langley, and Colwell, Gene and Hartley, James Georgia Institute of Technology.

48.) Phase Change Water Recovery for Space Station Parametric Testing and Analysis. 860986. Zdankiewicz, Ed and Chu, James, Life Systems, Inc.

49.) The Space Station Air Revitalization Subsystem Design Concept. SAE 871448. Ray, Ogle, Tipps, Carrasquillo, and Wieland, Life Support & Environmental Branch NASA Marshall Space Flight Center.

Excellent source of information on the ARS. This paper describes the current status of the ECLSS Air Revitalization Subsystem (ARS). ARS design is outlined, performance requirements are provided and evaluations of the relative merits of each of the subsystem options. Also computer models which analyze individual subsystem performance are discussed. The level of MFSC testing is summarized.

50.) A Membrane-Based Subsystem for Very High Recoveries of Spacecraft† Waste Waters. 860984. Ray, Retzlaff, Radke, and Newbold, Bend Research, Inc. Bend, OR and Price, NASA Johnson Space Center.

51.) Concepts for the Evolution of the Space Station Program. 860972. Michaud and Miller, General Electric/Management and Technical Services Co. Houston, TX and Primeaux NASA Johnson Space Center.

52.) Pre- and Post-Treatment Techniques for Spacecraft Water Recovery. 860982. Putnam and Colombo Umpqua, Research Co. Myrtle Creek, OR and Chullen, NASA Johnson Space Center.

53.) An Advanced Carbon Reactor Subsystem for Carbon Dioxide Reduction. 860995. Noyes, Hamilton Standard and Cusick, NASA Johnson Space Center.

54.) Integrated Waste and Water Management System. 860996. Murray, General Electric Co., Houston Operations and Sauer, NASA Johnson Space Center.

This 1986 paper generally describes the IWWMS (Integrated Waste and Water Management System) that was developed by the AEC, Air Force and NASA. The system utilized distillation and catalytic oxidation processes for purifying waste water and microbial digestion and incineration for

waste solids disposal. With the renewed interest in Space Station Freedom, this system was reviewed for applicability, updating and possible synergism with other life support systems.

55.) System Aspects of Columbus Thermal Control. 860938. Laux, Beckman and Lawson, MBB/ERNO Raumfahrttechnik GmbH.

56.) Hyperbaric Oxygen Therapy for Decompression Accidents -- Potential Applications to Space Station Operation. 860927. Pilmanis, University of Southern California, Catalina Hyperbaric Chamber.

57.) Columbus Life Support System and its Technology Development. 860966. Leiseifer, Skoog and Preiss, Dornier System GmbH, Friedrichshaten , FRG.

58.) A Study of Sabatier Reactor Operation in Zero "G". SAE 840936. Forsythe, Broome College, Verostko and Cusick Johnson Space Center, and Blakely, Hamilton Standard. July 1984.

This 1984 paper presents results of zero "G" computer model simulations of the Sabatier reactor operation. It concludes that the reactor will run significantly hotter in a zero "G" environment if cooling air flow is not increased to compensate for the loss of natural convection. It can be successfully operated in zero G with the three and five man loads for which it was designed. The requirement for motion of air in the inhabited areas of a Space Station Freedom would lead to improved performance. For eight and ten-man loads, increased cooling flow in the jackets and forced exterior cooling would improve the performance of the reactor. This may also be achieved by a larger reactor. the temperatures of the reactor exterior surfaces are affected more by the zero-gravity conditions than the interior catalyst temperatures. More recent papers have not shown the heat convection to be a problem. Possibly only of interest in a historical developmental aspect.

59.) Effects of Varying Environmental Parameters on Trace Contaminant Concentrations in the NASA Space Station Reference Configuration. 860916. Brewer, Vigyan Research Associates,Inc and Hall, NASA Langley Research Center.

60.) Space Station Life Support Oxygen Generation by SPE Water Electrolyzer Systems. 860949. Erickson and McElroy, Hamilton Standard, Windsor Locks, CT.

Solid Polymer Electrolyte (SPE) O2 generation by water electrolysis became practical in the late sixties with the introduction of fluorocarbon ion exchange membranes. Developed by Hamilton Standard under contract to NASA the SPE vapor feed electrolizer is capable of supplying 0.06 lbs./hr. of O2 at 3000 psi. A design used in nuclear submarines was modified to eliminate rotating equipment, the pre-deionizer, and associated maintenance. The design uses the energy in the high pressure hydrogen produced within the electrolyzer to pressurize the input process water 3000 psi. without the use of a mechanical pump.

61.) Integrated Air Revitalization System for Space Station. 860946. Boyda and Miller, Life Systems Inc. and Schwartz, Ames Research Center.

Life Science's produced a prototype ARS using EDC for CO2 removal, SFE for O2 generation, and Sabatier reactor for CO2 reduction. This integrated prototype was built and tested to investigate the effects of process interactions on the operation of component functions, and any benefits in terms of power, weight, and volume reduction.

This report contains drawings of subsystem components and design characteristics such as power requirements. Of special interest is the fact that the integrated system includes 72 sensors and 27 actuators. Details of these sensors are not provided in the drawings or text!

62.) Automated Subsystems Control Development. SAE 851379. Block, Honeywell Space and Strategic Systems Div. Heppner, Life Systems Inc. Samonski and Lance, NASA Johnson Space Center. July 1985.

This report, similar in content to doc. #111, describes the Automated Subsystems Control for Life Support Systems (ASCLSS) project. The system consists of a hierarchy of distributed controllers implemented with 1750A microprocessors and a high speed busing network.

63.) Nuclear Powered Submarines and the Space Station: A Comparison of ECLSS Requirements. 860945. Rossier, Martin Marietta Aerospace.

An interesting article that doesn't contain much information of use to us. Basically a comparison/contrast of ECLSS subsystems. There are fundamental differences in mission, environment, and resupply logistics for the two vehicles.

"At present, specific operational parameters,design requirements, and resource availability for each vehicle dictate differing technologies for some (I'd say most) aspects of ECLSS design."

64.) EDC Development and Testing for the Space Station Program. 860918. Boyda and Hendrix, Life Systems, Inc.

The Electrochemical Carbon Dioxide Concentration (EDC) has also been called the Electrochemically Depolarized Cell. This subsystem produced by Life Systems Inc. under contract to NASA utilizes an electrochemical cell to transfer CO_2 from low partial pressure atmospheres into a stream of H_2 and CO_2 suitable for reduction processing.. The EDC is fairly light (5 to 10 lbs) and is a net producer of power (54 to 71 watts). This paper gives a good comparison of CO_2 removal technologies, the EDC, SAWD, 2BMS (carbon mol sieve), and 4BMS (zeolyte) on page 84. The EDC is the lightest, most compact, and a net power producer, and appears to be the most desirable technology.

65.) Evaluation of Regenerative Portable Life Support Systems Options. 860948. Ciocca, Gruman Space Systems.

This Grumman Space System report gives baseline MMU support that must be supplied by the Space Station EVA Support Subsystem (ES). 2000 EVA hrs. per year are projected for payload servicing and station maintenance with 50% growth over the next five years. The Space Station ES would be similar to the STS facility with additional advanced electronics for built in test capability, caution and warning, communications and heads up display.

66.) An Evolutionary Approach to the Development of a CELSS Based Air Revitalization System. 860968. Huttenbach and Pratt, Nelson Space Services, Ltd. and Bucke LH Bioprocessing, Ltd.

The Controlled Ecological Life Support System (CELSS) is designed to closely mirror the biological/ecological CO_2 reduction and O_2 generation processes found on earth as an alternative to conventional physio-chemical methods on long duration missions. This Nelson Space Services research report reviews the limitations of conventional systems and presents details for a solar powered Algal bioreactor on a comparative basis. This is basic pioneering work for a Mars mission. The technology is not well studied and is encountering some resistance from engineering. Systems of this type are not baselined for station use.

67.) Physiological Requirements and Pressure Control of a Spaceplane. 860965. Lemaignen, Fagot, and Weibel, Avions Marcel Dassault-Brequet Aviation Saint Cloud, France.

This paper presents baseline data from a computer model for an Atmosphere control and supply subsystem (ACS) for the European space plane Hermes. The model uses first order D.E.'s for each of four gasses in the cabin atmosphere.

68.) Development of a Water Recovery Subsystem Based on Vapor Phase Catalytic Ammonia Removal (VPCAR). 860985. Budinkas and Rasouli, GARD Div Chamberlain Mfg. Corp. and Wydeven, NASA Ames Research Center.

The VPCAR process was developed to produce potable water from unpretreated urine! The process is based on a catalytic chemical process whereby the impurities vaporizing with the process water are oxidized to innocuous gasses products. The VPCAR water recovery subsystem consists of the following components:

* Hollow fiber membrane evaporator
* Vapor blower/compressor for gas stream recycling
* Catalytic reactor for ammonia & hydrocarbon oxidation
* Porous tube water vapor condensor
* Catalytic N_2O decomposition Reactor

The breadboard system produces higher quality water, has lower requirements for expendables, and accumulates less sludge. Even with non-optimized commercial components, the VPCAR is competitive with the TIMES & VCD in weight, volume and power requirements.

69.) Air Evaporation Closed Cycle Water Recovery Technology -- Advanced Energy Saving Designs. 860987. Morasko, AiResearch Manufacturing Co. Torrance, CA; Putnam, Umpqua Research Co., Myrtle Creek, OR; Bagdigian, NASA Marshall Space Flight Center.

A wick feed air evaporator is presented as an alternative to the TIMES & VCD. A preprototype unit was produced by Airesearch Manufacturing Corp. in Conjunction with Umpqua Research under MSFC contract. The system is capable of 100% water recovery from urine, wash water, RO brine, etc. It utilizes a circulating air stream, air heater, wick evaporator, and condensing heat exchanger for reclaiming process water from heavily contaminated feed streams. Wicks load up with solids until capillary action is severely affected, the wick pads are then replaced and spent pads with the solid contaminants are placed in waste management for return. The system is light, rugged, and requires little power. Unfortunately wick pads must be delivered and returned from orbit indefinitely.

70.) Status of the Space Station Environmental Control and Life Support System Design Concept. 860943. Ray and Humphries, Life Support & Environmental Branch NASA Marshall Space Flight Center.

This paper reviewed the status of the Space Station Freedom ECLSS as of 1986. This is an annual type report similar to that reported in document no. 88. It shows similar outlines of ECLSS subsystems and their functions. Table 2 has respirable atmosphere and water requirements. It discusses the reasons for deciding on the configuration of the Space Station Freedom and how ECLSS interfaces with other systems and modules. In configuration studies it was decided that closed loop configuration should be used to lower weight/volume requirements and lower resupply penalties. The distribution of the subsystems was studied. It was determined that FDS, ACS, and THC should be distributed equally in the two U.S. modules. Four AR and potable water recovery systems (two in each U.S. module) should be used. There are also tables of the ECLSS resource summary, resource requirements, and an 8 member crew mass balance presented.

71.) Enhanced Evaporative Surface for Two-Phase Mounting Plates. 860979. Grote, Stark and Tefft, Mc Donnell Douglas Corp. St. Louis, MO.

72.) A Space Station Utility -- Static Feed Electrolyzer. 860920. Larkins, Wagner, and Gopikanth, Life Systems, Inc.

The Static Feed Elctrolyzer O_2 generation subsystem developed by Life Systems Inc. under contract for NASA, could generate O_2 from water sources for use in ECLSS, Electrical power systems (EPS), and Extravehicular activities (EVA). In the ECLSS system alone the SFE might be used to generate metabolic oxygen, to provide reactants for CO_2 removal, and to generate hydrogen for CO_2 reduction. An SFE is also capable of generating H_2/O_2 propellents for propulsion and reboost systems.

The main focus of this report is to investigate systems commonality benefits. What weight and power benefits would arise from integrated SFE systems servicing several other station subsystems? Their conclusion was; "From every perspective user to system to design, the benefits of commonality introduced by using an integrated SFE O_2/H_2 generation should be viewed as a utility to satisfy a wide range of space station requirements."

The report includes drawings, photographs, and a technical description of the system. The module consists of a series of individual electrochemical cells stacked fluidically in parallel and connected electrically in series.
The following control and support hardware is required:

(1) Coolant Control Assembly - Provides a constant flow of controlled, variable temperature liquid coolant to the electrochemical module.
(2) Pressure Control Assembly -Maintains absolute subsystem pressure, controls differential pressures required to establish and maintain the liquid/gas interfaces within the cell cavities and controls initial pressurization and depressurization.
(3) Fluids Control Assembly - Controls and monitors the pressure and flow of water and N2 during steady state electrolysis and mode transitions.

73.) Regenerative Life Support System Hardware Testing -- A Summary. 860941. Reysa, Boeing Aerospace Operations, Houston, TX.

Quite a good report on the history and results of ECLSS competing subsystem technologies comparative testing.The following points are worth noting :
1. The SFE was selected because it did not require a dynamic H2O/H2 separator which had to be used in the SPE to prevent pump vapor lock. Baseline configuration designers chose the SFE to significantly reduce mechanical complexity and maintenance.

74.) Habitation Module for the Space Station. 860928. Johnson, Wolbers, and Miles; Mc Donell Douglas Aeronautics Co. Huntington Beach, CA.

75.) Space Station Health Maintenance Facility. 860922. Harvey et. al. Lockheed Missiles & Space Co. Inc. Sunnyvale, CA.

76.) Design of an Oxygen Sensor with Automatic Self-Testing and Calibration Capability. 860919. Kutschker and Taylor; Leeds & Northrup Instruments, A Unit of General Signal, and Cusick, NASA Johnson Space Center.

77.) Analysis and Composition of a Model Trace Gaseous Mixture for a Spacecraft. 860917. Schwartz and Oldmark, NASA Ames Research Center.

78.) An Expert Systems Approach to Automated Fault Diagnostics. SAE 851380. Lance and Malin, NASA Johnson Space Center. July 1985.

An excellent report for us! A KBS fault isolation and recovery program called "FIXER" has been developed by Johnson Space Center (JSC) in Inellcorp's KEE tool for the ARS CO_2 removal subsystem, the electrochemically depolarized cell (EDC). This EDC version termed "CS-1" in the text was developed by Life Systems Inc. This EDC Hardware is described in Doc.#64. Their model did not treat multiple faults or fluid leaks, but was rather sophisticated in other ways. It was designed to operate in parallel with the actual hardware controller and was required to recover from potential fault conditions before the EDC module controller interupted operation at onset of a red-line condition.

They chose a relatively small,simple, and well developed subsystem (hardware had been delivered) and their treatment reflects this. Their short, 12 man week effort produced a tool capable of extending periods of autonomous operation of the EDC in spite of any of 23 possible single fault conditions.

79.) Utility of an Emulation and Simulation Computer Model for Air Revitalization System Hardware Design, Development, and Test. SQE 851377. Yanosy; Hamilton Standard Div. United Technologies Corp, and Rowell; NASA Langley Research Center.

80.) Integrated Waste and Water Management System. 860996. Murray; General Electric Co. Houston Operations and Sauer NASA Johnson Space Center.

81.) Environmental Control and Life Support Technologies for Advanced Manned Space Missions. 860994. Powell and Wynveen; Life Systems Inc. and Lin; NASA Johnson Space Center.

This paper is fairly outdated now. It presents some of the preliminary results of the study program of JSC to define ECLSS requirements for advanced space missions, identify unique mission drivers, develop trade methodology, assess existing ECLSS technology capabilities, identify new ECLSS technology needs, and establish a technology R&D plan. It also provides a brief history of the ECLSS throughout the U.S. manned space program. Table 5 lists performance requirements, but these are updated in other publications. Table 7 identifies ECLSS Mission Drivers by Mission Location and identifies those that are unique. They conclude that mission duration and crew size are large enough now to justify the use of regenerative ECLSS technologies, that these would lead to significant savings in initial and operational costs, but would take years of R&D efforts to obtain. Potential missions were identified and will require ECLSS technologies that avoid expendables and large resupply weight penalties.

82.) Atmospheric Contaminant Monitoring and Control in an Enclosed Environment. SAE 881094. Strack, Electric Boat Division, General Dynamics Corp. July, 1988.

Not very specific on use in space. The paper discusses the major contaminants expected to be found, discusses monitoring and control methods - but mostly based on experience in submarines. Very general about space environment applications.

83.) A Computer Aided Engineering Tool for ECLSS Systems. SAE 871423. Bangham, McDonnell Douglas Astronautics Co., Huntsville, AL and Reuter, Life Support Branch, Systems Analysis and Integration , NASA MSFC. .

84.) G189 Computer Program Modeling of Environmental Control and Life Support Systems for the Space Station. SAE 871427. Baker, So, and DeBarro, Space Station Systems Div. Rockwell International Corp. July, 1987.

This is another presentation of the material in Doc.# 18.

85.) Test Results of a Shower Water Recovery System. SAE 871512. Verostko et. al. NASA Johnson Space Center, and Reysa, Boeing Aerospace Operations, Houston, TX. July, 1987.

A shower test was conducted at JSC in which waste water was reclaimed and reused. The waste water was purified using reverse osmosis followed by filtration through activated carbon and ion exchange resin beds. The reclaimed waste water was, after modification, maintained free of microorganisms by using both heat and iodine. This paper discusses the limited effectiveness of using iodine as a disinfectant and the evaluation of a Space Station Freedom candidate soap for showering. There is a description of the RO used and the Umpqua unibeds used. They concluded that iodine was determined to not be an all inclusive disinfectant for all microorganisms. *P. Capacia* survived in the Shower Water Recovery System (SWRS) storage tanks disinfected with iodine. After modifications the use of heat disinfection at 185^{o}F for 3 hours was shown to be effective and necessary for waste water recovery systems. They also concluded that RO with post-treatment provided acceptable recovered shower water for recycling. There were early breakthroughs of organic impurities in the Unibeds, this was remedied by larger sorption beds. Finally the soap may cause a gel layer to form on the RO membrane, further testing is recommended on the soap. During reuse test the water had an odor whose source needs to be identified.

86.) Initial Results of Integrated Testing of a Regenerative ECLSS at MSFC. SAE 871454. Jackson and Worden, Boeing Aerospace Co. and Johnson, AiResearch Mfg. Co. July, 1987.

This paper gives the preliminary test results for integrated testing of ECLSS. Subsystems are described and plans for future testing outlined. All of this information is updated or covered in other articles already incorporated into the final report.

87.) Control/Monitor Instrumentation for Environmental Control and Life Support Systems Aboard the Space Station. 861007. Heppner, Khoury and Powell, Life Systems, Inc.

88.) Preliminary Design of the Space Station Environmental Control and Life Support System. 881031. Reuter, Turner and Humphries, Life Support Branch, NASA MSFC.

Excellent review article of status of the seven ECLSS subsystems with their brief descriptions and purposes. Discussion of "Safe Haven" and how this has affected the physical distribution, sizing, and interrelationship of subsystems. Some discussion of technologies still being developed and choices that will need to be made (may be useful in future technologies section of final report.

89.) Comparison of CO2 Reduction Process -- Bosch and Sabatier. SAE 851343. Spina and Lee, Life Systems, Inc. Cleveland, OH. July, 1985.

90.) A Study of the Sebatier-Methanation Reaction. SAE 740933. Verostko, NASA Johnson Space Center, and Forsythe, Broome College. July-August, 1974.

91.) Regenerative Life Support Program equipment Testing. SAE 881126. Boehm, Boynton and Mason, Hamilton Standard Division, United Technologies Corp. July, 1988.

This paper describes the integrated systems metabolic control testing of 4 subsystems developed by Hamilton Standard division of United Technologies: TIMES, Sabatier, SAWD, and SPE.

92.) Initial Development and Performance Evaluation of a Process for Formation of Dense Carbon by Pyrolysis of Methane. SAE 851342. Noyes, Hamilton Standard, and Cusick, NASA Johnson.

93.) Phase Change Water Processing for Space Station. 851346. Zdankiewicz, Life Systems, Inc. and Price, NASA Johnson.

94.) Water Quality Monitor for Recovered Spacecraft Water. SAE 851347. Ejzak, Astro Resources International Corp., and Price, NASA Johnson.

This paper describes a TOC analysis system based upon ultra-violet adsorption. Previous attempts to measure low levels of TOC involve the use of expendable and potentially dangerous chemical reagents. The unit currently under evaluation can handle extremely low level (2ppm) on a continuous basis. The sample is totally unchanged after exiting the unit. This state-of-the art breadboard shows promise. This 1985 paper is very preliminary. Will look for more recent articles on TOC analysis.

95.) Static Feed Water Electrolysis System for Space Station O_2 and H_2 Generation. SAE 851339. Larkins and Kovach. Life Systems, Inc.

This paper describes the SFE subsystem for oxygen generation on the Space Station Freedom. The overall system dynamics and schematics are provided as well as development testing up to this point. Other documents have more up to date information on the status of this technology.

96.) An Expert Systems Approach to Automated Maintenance for a Mars Oxygen Production System. SAE 881056. Haung, Wei, Ash, and Ho, Dept. of Mechanical Engineering & Mechanics, Old Dominion Univ., Norfolk, VA.

97.) Maturity of the Bosch CO2 Reduction Technology for Space Station Application. SAE 880995. Wagner; Life Systems Inc., Carrasquillo: NASA MSFC, and Edwards and Holmes; Boeing. 1988.

This paper describes the evolution of the Bosch CO_2 reduction subsystem. It concludes that the Bosch process is reaching a level of technological maturity demonstrating its viability for Space Station Freedom application. Some work remains before flight hardware is constructed, particularly improvements which will optimize weight, power, volume and maintainability.

The Bosch technology is promising because there is no on-board gaseous storage or overboard venting required, and it is potentially 100% efficient.

The Bosch process occurs at 426 to 726^{o}C in the presence of a catalyst. Carbon dioxide combines with H_2 and produces carbon and water vapor in an exothermic reaction. A recirculating loop is required to attain good conversion efficiencies.

A Bosch II design is currently in operation at the NASA MFSC.This design includes a cold seal Bosch reactor which eliminated the tremendous heat loss at the closure interface, and also eliminated the need for a vacuum interface. The entire process is contained within a disposable carbon cartridge. There is a recuperative heat exchanger that maximizes the Bosch thermal efficiency.

The Bosch subsystem is designed for completely automated operation. A Control Monitor incorporating microcomputer software technologies is used for automatic mode. The computer is required when switching between operating modes and for fault detection, fault isolation, fault prediction and built-in diagnostics for subsystem verification.

98.) Carbon Dioxide Reduction Processes for Spacecraft ECLSS: A Comprehensive Review. SAE 881042. Noves, Hamilton Standard.

99.) Using Hardware to Test the Space Station Water Reclamation and Management Subsystem in Zero-G. SAE 881018. Williams, Rockwell Shuttle Operations Company.

100.) Two-Bed Carbon Molecular Sieve Carbon Dioxide Removal System Feasibility Testing. SAE 880993. Kay, R.J. and Tom, R., Allied-Signal Aerospace, AiResearch Los Angeles Div, Torrance, CA.

101.) Environmental Control and Life Support Testing at the Marshall Space Flight Center. SAE 871453. Schunk and Humphries, Life Support Branch, NASA MSFC.]

This paper addresses the in-house MSFC development test program including both subsystem and system level activities. THC, ACS, and FDS were not emphasized because of previous extensive flight experience. EVA support is also not addressed. AR and WRM were the groups being addressed, with WM being performed at contractor facilities. Specific issues were water and oxygen reclamation and trace contaminant control.

Development work in 1986-1987 was being done on a multifiltration unit for washwater recovery, and multifiltration tests on potable water reclamation. Air evaporation phase change urine reclamation was done by the contractor.

System level tests included interactive testing of selected air revitalization and water reclamation subsystem equipment. The simulator and area is known as the Core Module Integration Facility (CMIF). Five subsystems were selected for system testing: TIMES (Thermoelectric Integrated Membrane Evaporation Subsystem), the 4-Bed Molecular Sieve subsystem, the SFE (Static Feed Electrolyzer) subsystem, the Sabatier subsystem, and the TCCS (Trace Contaminant Control Subsystem) Phase II testing, which was to conclude in 1987, contained five regenerative ECLSS subsystems located inside the simulator: a TIMES water reclamation subsystem, a SFE oxygen generation subsystem, a Sabatier carbon dioxide reduction subsystem, and a TCCS. Support hardware included a metabolic simulator, a near real time water quality monitor and a TSA (Test Support Accessory) for the SFE subsystem.

102.) An Efficient Air Evaporation Urine Processing System for Space Station. SAE 881034. Madsen; Allied-Signal Aerospace, and Putnam; Umpqua Research Company.

103.) Air and Water Quality Monitor Assessment of Life Support Subsystems. SAE 881014. Whitley, Carrasquillo, Holder and Humphries, NASA MSFC.

This paper describes the status of the MSFC test program for the air revitalization and water recovery management subsystems. As of this date, the AR and WRM subsystems have not been defined. There was a Phase B preliminary design completed in 1986. ECLSS subsystem competitors were gathered at MSFC for testing prior to final selection. Independent and system level testing is being done. These tests included an oxygen reclamation subsystem string including the 4-bed Molecular Sieve (4-BMS) CO_2 removal unit, the Sabatier CO_2 reduction unit, and the KOH Static Feed Electrolyzer (SFE) oxygen generation unit. Also tested was the Thermoelectric Integrated Membrane Evaporation System (TIMES) urine water recovery unit and a Trace Contaminant Control System (TCCS). Multifiltration and reverse osmosis were not available.

The goals of the tests were limited - the design did not incorporate any microbial control features and sample ports were not of an aseptic design, chemical evaluation was not done in a rigorous fashion and no effort was made in the test system design to meet hygiene water quality requirements for the TIMES product water.

There were four major test activities in 1987: one independent subsystem test for each air and water subsystem and three separate integrated system tests. The first integrated test consisted of the air revitalization loop, the second and third termed Metabolic Control Test of 3 day duration, and the fourth an Extended Metabolic Control Test of 6 day duration. Results of theses tests and suggestions for future modifications were discussed. In conclusion, improved sampling techniques are needed to eliminate air contamination, a better method of quantifying water vapor percentage must be established, a real-time monitoring of ECLSS gases is needed among other things.

104.) Advancements in Water Vapor Electrolysis Technology. SAE 881041. Chullen, NASA Johnson Space Center, and Heppner and Sudar, Life Systems, Inc.

105.) Air Revitalization System Study for Japanese Space Station. SAE 881112. Otsuji, Hanabusa, Etoh and Minemoto; Mitsubishi Heavy Industries, Ltd., Japan.

106.) Technology Demonstrator Program for Space Station Environmental Control Life Support System. SAE 871456. Adams, Platt, Claunch, and Humphries, NASA MSFC>

107.) Space Station Environmental Control and Life Support System Distribution and Loop Closure Studies. SAE 8609452. Humphries, James, Reuter, and Schunk; NASA MSFC.

This paper addressed the distribution among the modules of the ECLSS subsystems. The module resource requirements and safety implications, particularly with regard to safe haven operations was discussed. It also addresses the degree of loop closure, and the recommendation to close both the oxygen and water recovery loops. To determine the distribution of subsystems it was first determined whether the ducting and plumbing sizes would work in centralization configuration. Second, the number of units, design capacity, and physical location of the subsystems was examined.

Safe haven is defined as the condition necessary to ensure survival of the crew for 28 days, while rescue is achieved. A safe haven operating condition can be instigated after two non-repairable failures of a given safety-critical subsystem, or after the loss of any single module. Because of safe haven, any centralized subsystem had to be physically located in two modules. Figure 18 shows the recommendations for whether a subsystem is physically centralized or distributed, and the locations of the subsystems. It was recommended that temperature control and intramodule ventilation be distributed, therefore each module would need a subsystem. Water, oxygen, carbon dioxide control, and contaminant control could be centralized. Humidity control was also distributed. Fire detection and suppression, module repressurization, and vent, relief and dump capabilities are required in each module. Hygiene water should be centralized. The air revitalization and potable water reclamation systems should be centralized, and these should be located in the two U.S. modules to satisfy safe haven requirements,.

108.) Controlling Real-Time Processes on the Space Station with Expert Systems. SPIE Vol. 729 Space Station Automation II (1986). Leinweber, David; LISP Machine Inc. Manhattan Beach, CA, and Perry, John; OAO,Inc Segundo, CA. 1986.

109.) The Role of Expert Systems on Space Station. Proceeding of Conference held in Geneva in May 1986. Sloggett, Environmental and Space Systems Group, Software Sciences, UK.

110.) System Autonomy Hooks and Scars for Space Station. SPIE Vol. 851, Space Station Automation III (1987). Starks and Elizandro, East Texas State University, CS Dept.

111.) Prototype Space Station Automation System Delivered and Demonstrated at NASA. NASA Conference Publication 2492. Block, Honeywell Space and Strategic Avionics Div., Clearwater, FL.

The Automated Subsystem Control for Life Support Systems (ACLSS) was developed by Honeywell and Life Systems Inc., as a proof of concept of a generic automated controller for Space Station subsystems. This group chose the ARS subsystem (they call it the ARG, air revitalization group) to develop a proof of concept model.

The developers claim "the delivered ACLSS demonstrated the automation of 1) three complex life support processes; 2) the monitoring and reporting of ARG system and process status, warning, and alarms; 3) the system event logging; 4) the fault detection and system safety; and 5) the calculation and evaluation of the current system operational performance parameters and efficiencies.

112.) Challenges in the Development of the Orbiter Atmospheric Revitalization Subsystem. NASA Conference Publication 2342. pt. 1. Prince, NASA Johnson; Swider et.al., Hamilton Standard; Ord and Walleshauser, Moog Inc. and Gibb, Rockwell International.

Details of THC and ACS subsystems for the Space Shuttle are presented in this report , with particular emphasis on multimission capabilities of pumps and separators. Systems that require gravity driven fluid flow or convection cooling fail quickly in low g use, and some ingenious work-arounds are discussed.

Specifically addressed are rotating elements, such as motors and liquid separators; and several pressure and atmosphere control components. Of particular interest is a valve position indicator discussed on page 421, and the flow sensor on pg. 422.

113.) Other Challenges in the Development of the Orbiter Environmental Control Hardware. NASA Conference Publication 2342 pt. 1. GIbb and McIntosh, Rockwell International.

This Rockwell Int. report discusses several problems encountered with Space Shuttle ECLSS subsystems, specifically the ammonia boiler system (ABS), smoke detector, water hydrogen separator, and the waste collection system (WCS). Of particular interest to us are the ABS, a heat exchanger to remove waste heat from avionics and other orbiter systems; the smoke detector, an FDS component; and the WCS, a WM subsystem.

At altitudes below 120,000 ft. the ABS provides a means for rejecting waste heat loads into the atmosphere. When the ABS is operating, heat is transferred from the Freon 21 cooling loop by the evaporation of anhydrous ammonia, which is then vented overboard. Some similar system will be necessary to reject heat from space station systems, however overboard venting will probably not be acceptable.

A piezoelectric microbalance type smoke detector was originally proposed for orbitor use, but calibration problems resulting from the extreme sensitivity of this device necessitated its replacement with an ionization type detector.

The waste collection system has undergone several evolutionary modifications to alleviate the problems associated with low gravity elimination. This section is rather humorous to those who have not dealt with this problem, but proper function of this equipment is important to health and crew moral.

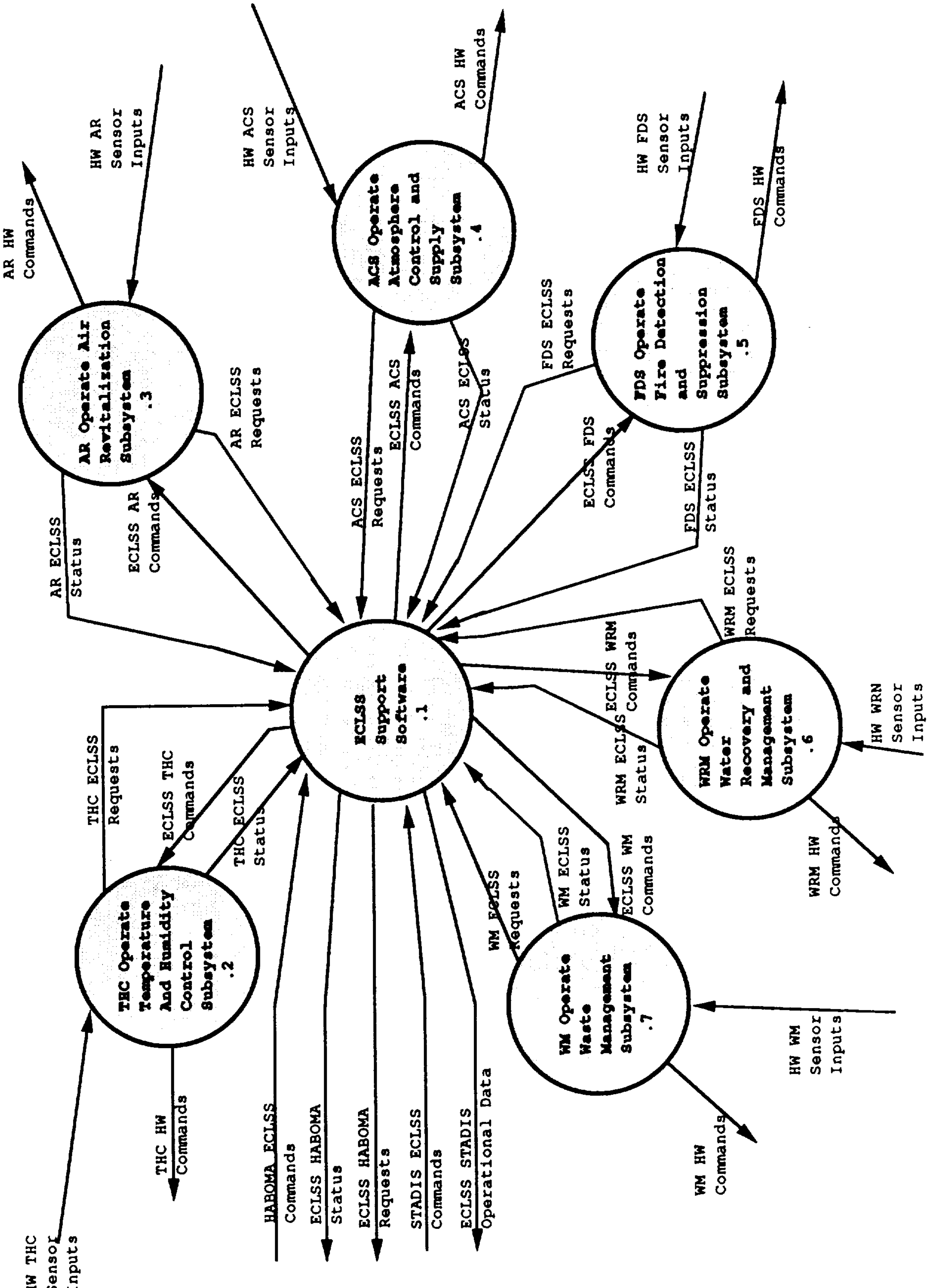
114.) Bagdigian, R., and W.R. Humphries. 1988. "Phase III CMIF Water Recovery System/Facility Design Requirements". November, 1988.

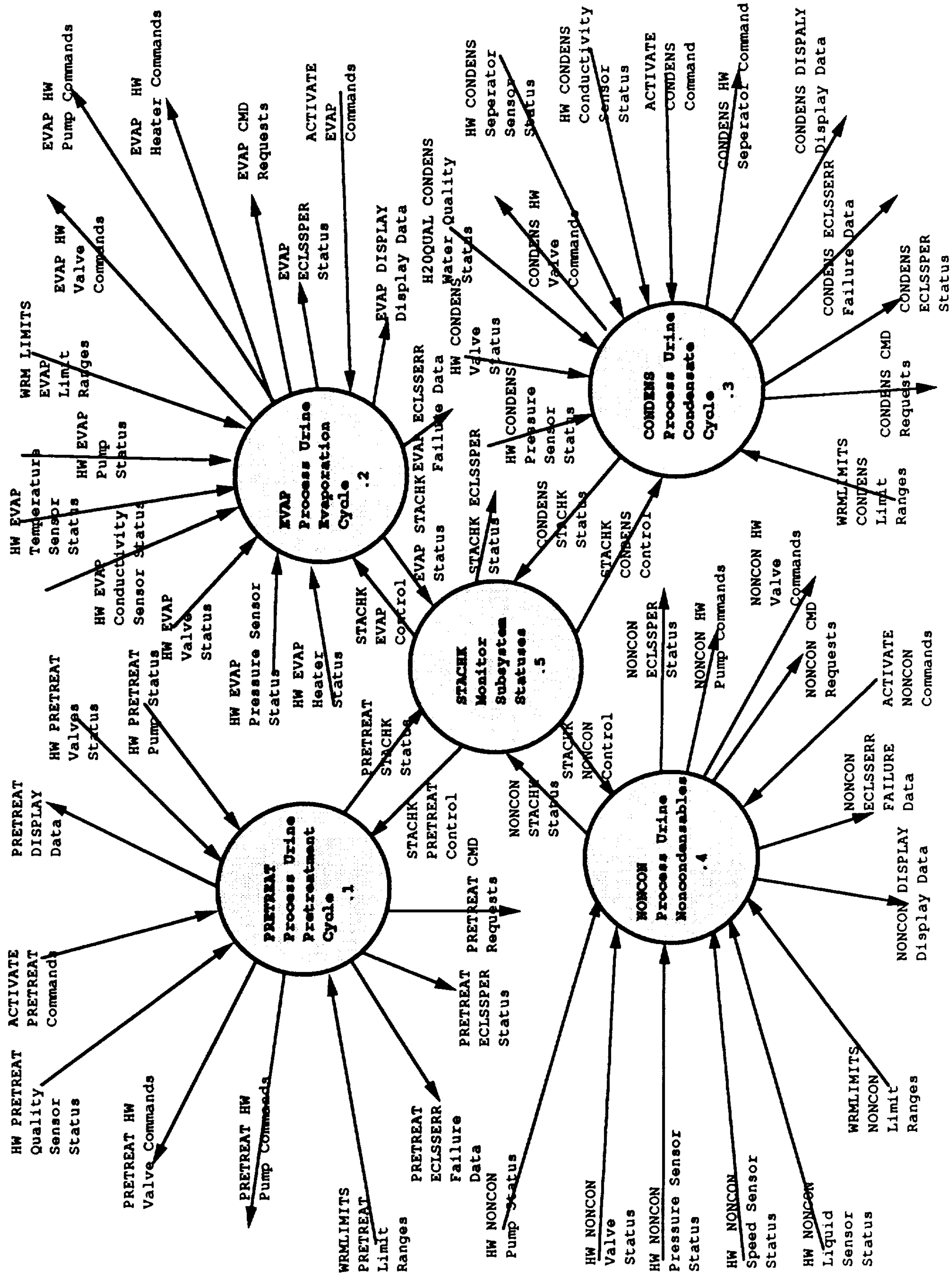
115.) Rogers, J.S., D.M. Rochowiak, B.L. Benson, and J.W. McKee. 1989. "A Diagnostic Prototype of the Potable Water Subsystem of Space Station Freedom ECLSS," UAH Research Report Number 824, Johnson Research Center, University of Alabama in Huntsville, November 1989.

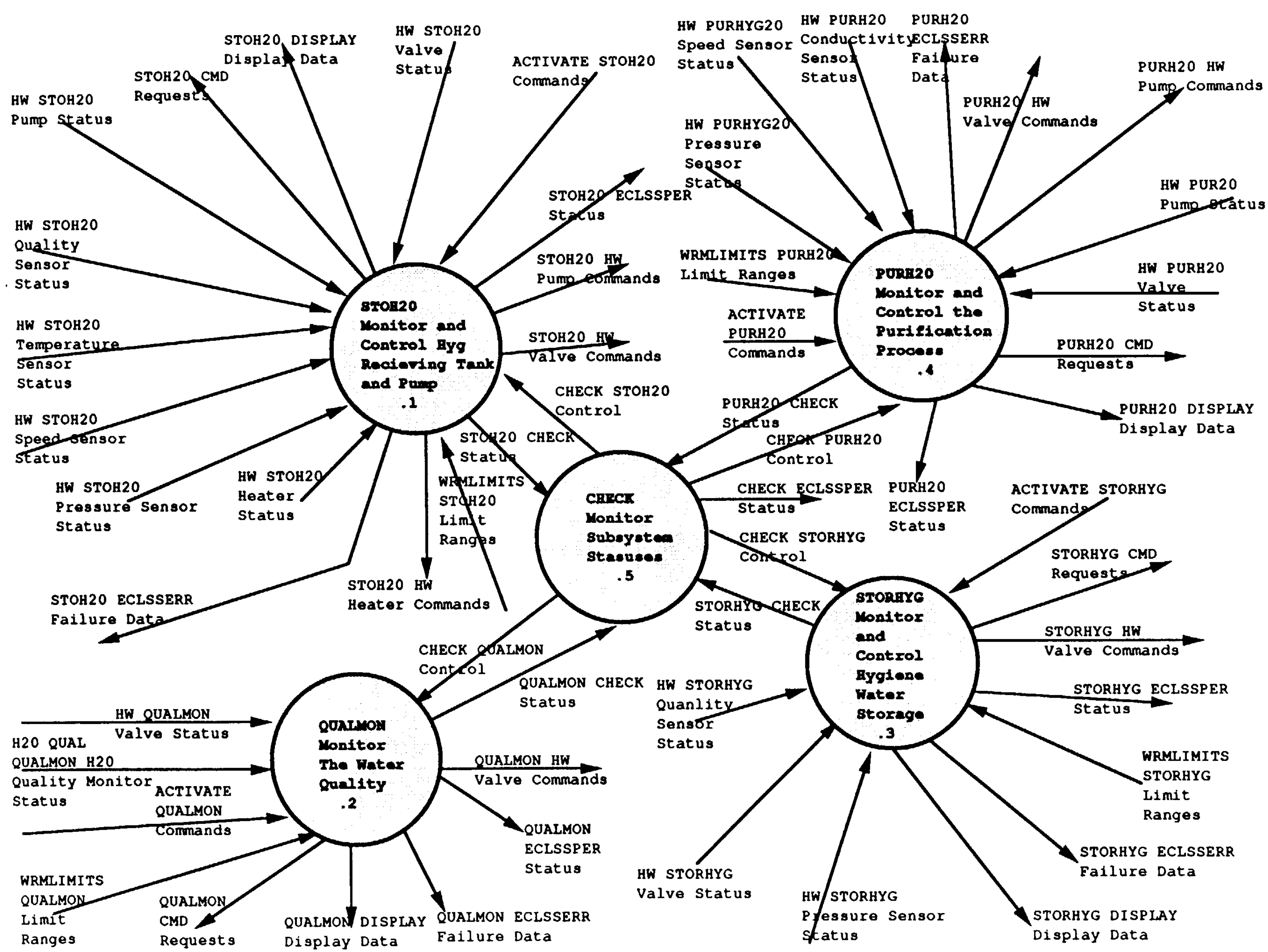
116.) Rochowiak, Daniel. 1989. "Final Report: Cooperating Intelligent Systems", prepared for Walt Mitchell, Systems Software Branch, Information and Electronic Systems Laboratory, Marshall Space Flight Center, UAH Research Report Number 804, prepared by the Johnson Research Center, University of Alabama in Huntsville, August 1989.

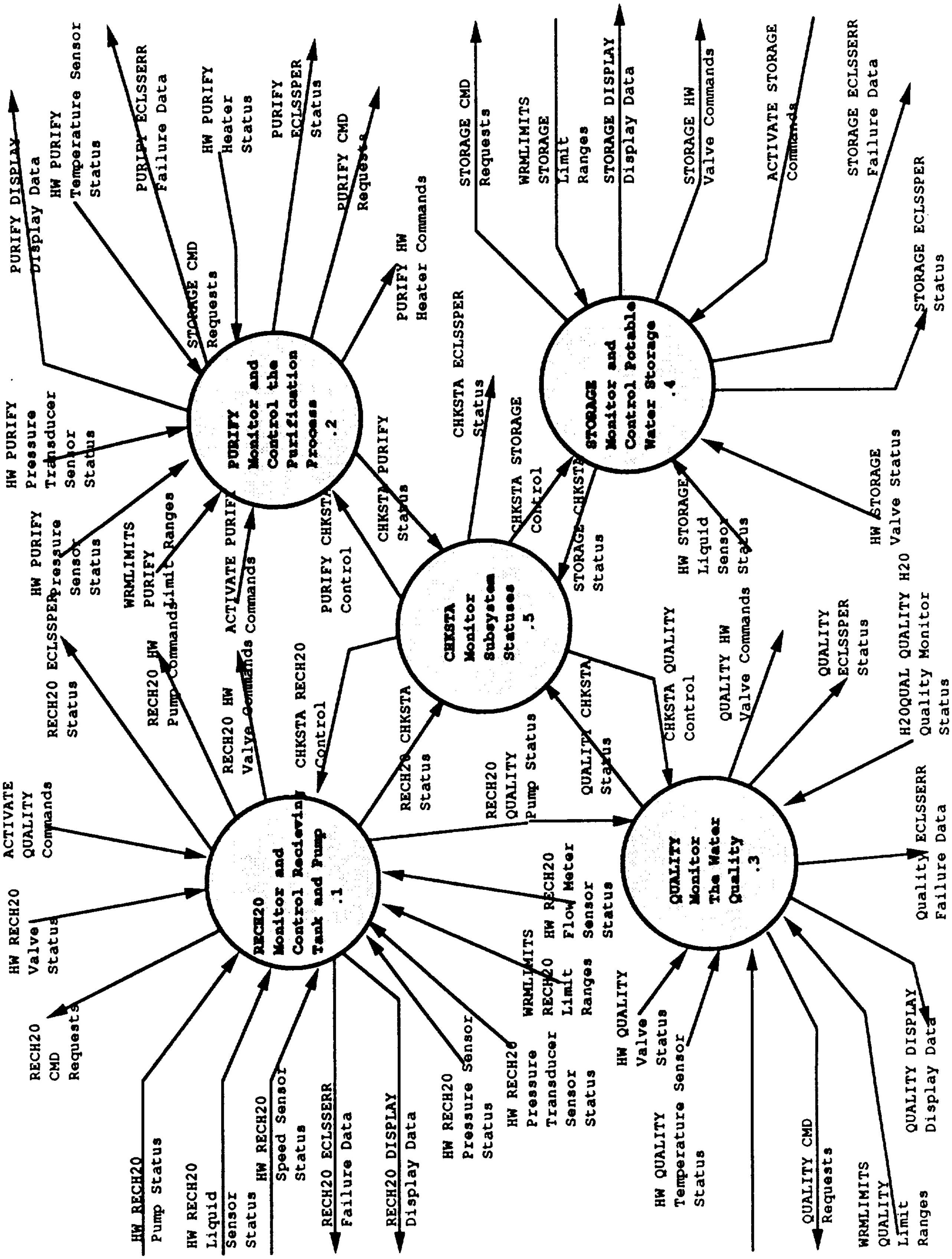
117.) Daley, Phillip and Allison Thornbrugh. 1989. "Using Neural Nets To Automate Knowledge Engineering," In Proceedings of Workshop on Knowledge Acquisition, IJCAI KA, (Detroit) pp 1-4, 1989.

APPENDIX B - Detailed Context Diagrams

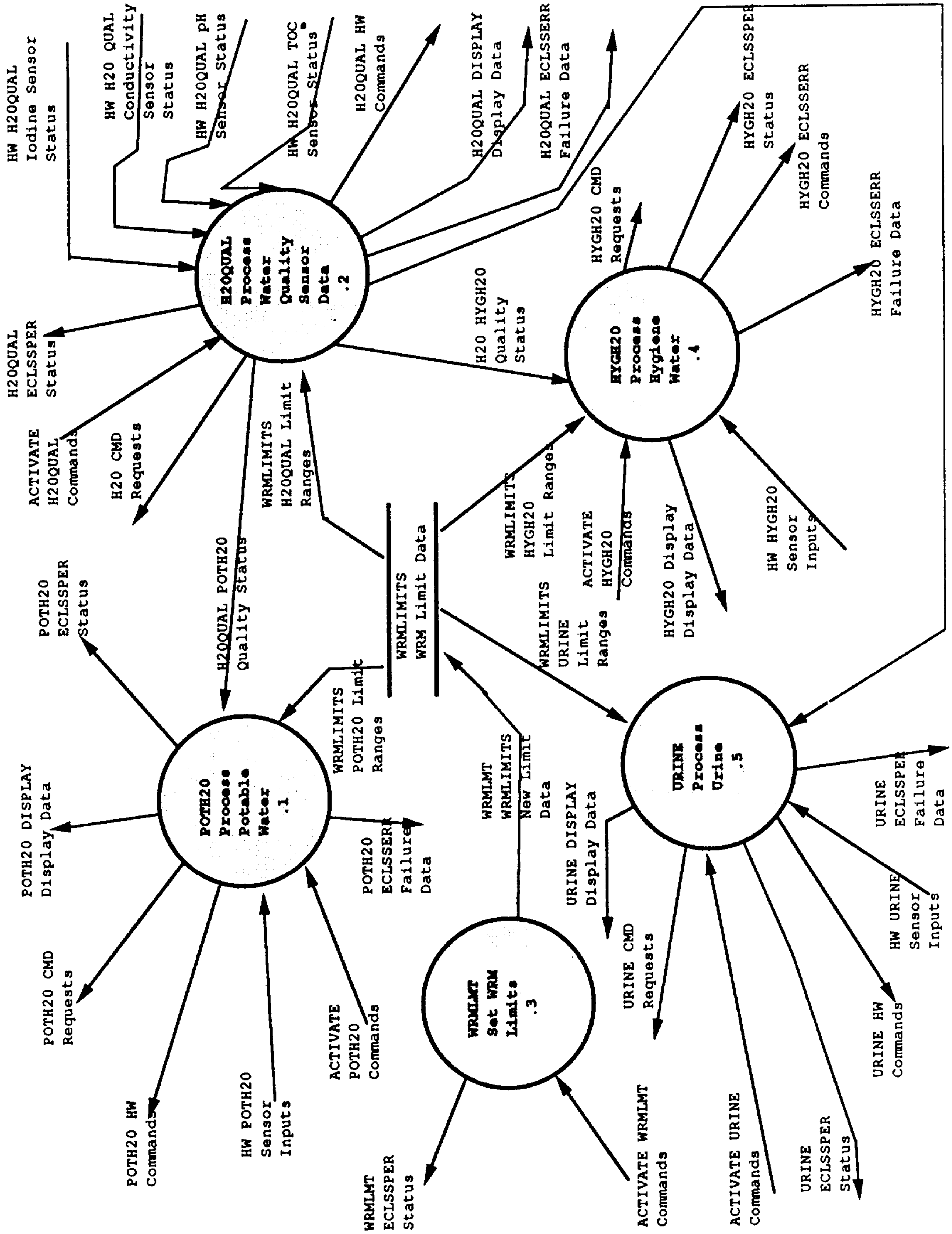

ECLSS Support Software .1
THC Operate Temperature And Humidity Control Subsystem .2
AR Operate Air Revitalization Subsystem .3
ACS Operate Atmosphere Control and Supply Subsystem .4
FDS Operate Fire Detection and Suppression Subsystem .5
WRM Operate Water Recovery and Management Subsystem .6
WM Operate Waste Management Subsystem .7
HW THC Sensor Inputs
THC HW Commands
THC ECLSS Requests
ECLSS THC Commands
THC ECLSS Status
AR HW Commands
HW AR Sensor Inputs
AR ECLSS Requests
AR ECLSS Status
ECLSS AR Commands
HW ACS Sensor Inputs
ACS HW Commands
ACS ECLSS Requests
ECLSS ACS Commands
ACS ECLSS Status
HW FDS Sensor Inputs
FDS HW Commands
FDS ECLSS Requests
ECLSS FDS Commands
FDS ECLSS Status
WRM ECLSS Requests
ECLSS WRM Commands
WRM ECLSS Status
HW WRN Sensor Inputs
WRM HW Commands
WM ECLSS Requests
WM ECLSS Status
ECLSS WM Commands
HW WM Sensor Inputs
WM HW Commands
HABOMA ECLSS Commands
ECLSS HABOMA Status
ECLSS HABOMA Requests
STADIS ECLSS Commands
ECLSS STADIS Operational Data

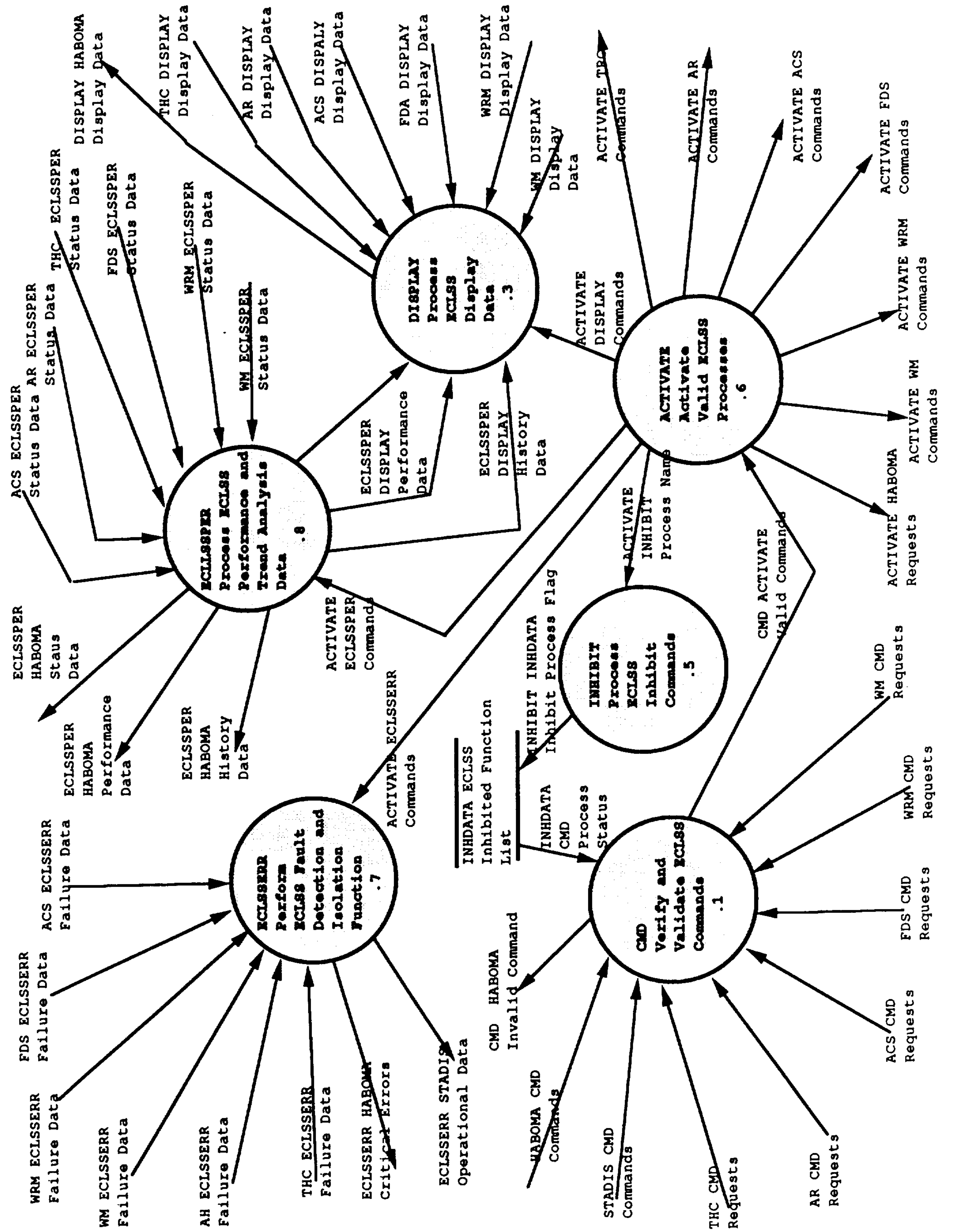

PRETREAT Process Urine Pretreatment Cycle .1
EVAP Process Urine Evaporation Cycle .2
CONDENS Process Urine Condensate Cycle .3
NONCON Process Urine Noncondensables .4
STACHK Monitor Subsystem Statuses .5
EVAP HW Pump Commands
EVAP HW Heater Commands
EVAP CMD Requests
ACTIVATE EVAP Commands
EVAP HW Valve Commands
EVAP ECLSSPER Status
EVAP DISPLAY Display Data
WRM LIMITS EVAP Limit Ranges
HW EVAP Pump Status
HW EVAP Temperature Sensor Status
HW EVAP Conductivity Sensor Status
HW EVAP Valve Status
HW EVAP Pressure Sensor Status
HW EVAP Heater Status
EVAL ECLSSERR Failure Data
STACHK EVAP Control
EVAP STACHK Status
H2OQUAL CONDENS Water Quality Status
HW CONDENS Seperator Sensor Status
HW CONDENS Conductivity Sensor Status
ACTIVATE CONDENS Command
CONDENS HW Seperator Command
CONDENS DISPALY Display Data
CONDENS HW Valve Commands
CONDENS ECLSSERR Failure Data
CONDENS ECLSSPER Status
HW CONDENS Valve Status
HW CONDENS Pressure Sensor Status
CONDENS CMD Requests
WRMLIMITS CONDENS Limit Ranges
STACHK ECLSSPER Status
CONDENS STACHK Status
STACHK CONDENS Control
NONCON HW Valve Commands
NONCON ECLSSPER Status
NONCON HW Pump Commands
NONCON CMD Requests
ACTIVATE NONCON Commands
STACHK NONCON Control
NONCON STACHK Status
NONCON ECLSSERR FAILURE Data
NONCON DISPLAY Display Data
WRMLIMITS NONCON Limit Ranges
HW NONCON Pump Status
HW NONCON Valve Status
HW NONCON Pressure Sensor Status
HW NONCON Speed Sensor Status
HW NONCON Liquid Sensor Status
PRETREAT STACHK Status
STACHK PRETREAT Control
HW PRETREAT Valves Status
HW PRETREAT Pump Status
PRETREAT DISPLAY Data
ACTIVATE PRETREAT Commands
HW PRETREAT Quality Sensor Status
PRETREAT HW Valve Commands
PRETREAT HW Pump Commands
WRMLIMITS PRETREAT Limit Ranges
PRETREAT ECLSSERR Failure Data
PRETREAT ECLSSPER Status
PRETREAT CMD Requests


STOH20
Monitor and
Control Hyg
Recieving Tank
and Pump
.1
QUALMON
Monitor
The Water
Quality
.2
STORHYG
Monitor
and
Control
Hygiene
Water
Storage
.3
PURH20
Monitor and
Control the
Purification
Process
.4
CHECK
Monitor
Subsystem
Stasuses
.5
HW STOH20 Pump Status
STOH20 CMD Requests
STOH20 DISPLAY Display Data
HW STOH20 Valve Status
ACTIVATE STOH20 Commands
STOH20 ECLSSPER Status
STOH20 HW Pump Commands
STOH20 HW Valve Commands
HW STOH20 Quality Sensor Status
HW STOH20 Temperature Sensor Status
HW STOH20 Speed Sensor Status
HW STOH20 Pressure Sensor Status
HW STOH20 Heater Status
STOH20 ECLSSERR Failure Data
STOH20 HW Heater Commands
WRMLIMITS STOH20 Limit Ranges
STOH20 CHECK Status
CHECK STOH20 Control
HW PURHYG20 Speed Sensor Status
HW PURH20 Conductivity Sensor Status
PURH20 ECLSSERR Failure Data
PURH20 HW Valve Commands
PURH20 HW Pump Commands
HW PURHYG20 Pressure Sensor Status
HW PUR20 Pump Status
WRMLIMITS PURH20 Limit Ranges
HW PURH20 Valve Status
ACTIVATE PURH20 Commands
PURH20 CMD Requests
PURH20 CHECK Status
CHECK PURH20 Control
PURH20 DISPLAY Display Data
CHECK ECLSSPER Status
PURH20 ECLSSPER Status
ACTIVATE STORHYG Commands
CHECK STORHYG Control
STORHYG CMD Requests
STORHYG CHECK Status
STORHYG HW Valve Commands
CHECK QUALMON Control
QUALMON CHECK Status
HW STORHYG Quanlity Sensor Status
STORHYG ECLSSPER Status
WRMLIMITS STORHYG Limit Ranges
HW QUALMON Valve Status
H20 QUAL QUALMON H20 Quality Monitor Status
QUALMON HW Valve Commands
ACTIVATE QUALMON Commands
QUALMON ECLSSPER Status
STORHYG ECLSSERR Failure Data
WRMLIMITS QUALMON Limit Ranges
QUALMON CMD Requests
QUALMON DISPLAY Display Data
QUALMON ECLSSERR Failure Data
HW STORHYG Valve Status
HW STORHYG Pressure Sensor Status
STORHYG DISPLAY Display Data



PURIFY Monitor and Control the Purification Process .2
RECH20 Monitor and Control Recieving Tank and Pump .1
CHKSTA Monitor Subsystem Statuses .5
STORAGE Monitor and Control Potable Water Storage .4
QUALITY Monitor The Water Quality .3
PURIFY DISPLAY Display Data
HW PURIFY Temperature Sensor Status
PURIFY ECLSSERR Failure Data
STORAGE CMD Requests
HW PURIFY Heater Status
PURIFY ECLSSPER Status
PURIFY CMD Requests
PURIFY HW Heater Commands
HW PURIFY Pressure Transducer Sensor Status
HW PURIFY Pressure Sensor Status
WRMLIMITS PURIFY Limit Ranges
ACTIVATE PURIFY Commands
PURIFY CHKSTA Control
CHKSTA PURIFY Status
CHKSTA ECLSSPER Status
CHKSTA STORAGE Control
STORAGE CHKSTA Status
STORAGE CMD Requests
WRMLIMITS STORAGE Limit Ranges
STORAGE DISPLAY Display Data
STORAGE HW Valve Commands
ACTIVATE STORAGE Commands
STORAGE ECLSSERR Failure Data
STORAGE ECLSSPER Status
HW STORAGE Liquid Sensor Status
HW STORAGE Valve Status
RECH20 ECLSSPER Status
RECH20 HW Pump Commands
RECH20 HW Valve Commands
CHKSTA RECH20 Control
RECH20 CHKSTA Status
RECH20 QUALITY Pump Status
QUALITY CHKSTA Status
CHKSTA QUALITY Control
QUALITY HW Valve Commands
QUALITY ECLSSPER Status
H2OQUAL QUALITY H20 Quality Monitor Status
Quality ECLSSERR Failure Data
ACTIVATE QUALITY Commands
HW RECH20 Valve Status
RECH20 CMD Requests
HW RECH20 Pump Status
HW RECH20 Liquid Sensor Status
HW RECH20 Speed Sensor Status
RECH20 ECLSSERR Failure Data
RECH20 DISPLAY Display Data
HW RECH20 Pressure Sensor Status
HW RECH20 Pressure Transducer Sensor Status
WRMLIMITS RECH20 Limit Ranges
HW RECH20 Flow Meter Sensor Status
HW QUALITY Valve Status
HW QUALITY Temperature Sensor Status
QUALITY CMD Requests
WRMLIMITS QUALITY Limit Ranges
QUALITY DISPLAY Display Data


H2OQUAL Process Water Quality Sensor Data .2
POTH2O Process Potable Water .1
WRMLMT Set WRM Limits .3
HYGH2O Process Hygiene Water .4
URINE Process Urine .5
WRMLIMITS WRM Limit Data
HW H2OQUAL Iodine Sensor Status
HW H2O QUAL Conductivity Sensor Status
HW H2OQUAL pH Sensor Status
HW H2OQUAL TOC Sensor Status
H2OQUAL HW Commands
H2OQUAL DISPLAY Display Data
H2OQUAL ECLSSERR Failure Data
H2OQUAL ECLSSPER Status
ACTIVATE H2OQUAL Commands
H2O CMD Requests
WRMLIMITS H2OQUAL Limit Ranges
H2OQUAL POTH2O Quality Status
H2O HYGH2O Quality Status
HYGH2O CMD Requests
HYGH2O ECLSSPER Status
HYGH2O ECLSSERR Commands
HYGH2O ECLSSERR Failure Data
WRMLIMITS HYGH2O Limit Ranges
ACTIVATE HYGH2O Commands
HYGH2O Display Display Data
HW HYGH2O Sensor Inputs
POTH2O ECLSSPER Status
WRMLIMITS POTH2O Limit Ranges
POTH2O DISPLAY Display Data
POTH2O ECLSSERR Failure Data
POTH2O CMD Requests
POTH2O HW Commands
HW POTH2O Sensor Inputs
ACTIVATE POTH2O Commands
WRMLMT WRMLIMITS New Limit Data
WRMLMT ECLSSPER Status
ACTIVATE WRMLMT Commands
WRMLIMITS URINE Limit Ranges
URINE DISPLAY Display Data
URINE CMD Requests
ACTIVATE URINE Commands
URINE ECLSSPER Status
URINE HW Commands
HW URINE Sensor Inputs
URINE ECLSSPER Failure Data



DISPLAY Process ECLSS Display Data .3
ACTIVATE Activate Valid ECLSS Processes .6
ECLSSPER Process ECLSS Performance and Trend Analysis Data .8
INHIBIT Process ECLSS Inhibit Commands .5
ECLSSERR Perform ECLSS Fault Detection and Isolation Function .7
CMD Verify and Validate ECLSS Commands .1
DISPLAY HABOMA Display Data
THC DISPLAY Display Data
AR DISPLAY Display Data
ACS DISPALY Display Data
FDA DISPLAY Display Data
WRM DISPLAY Display Data
WM DISPLAY Display Data
ACTIVATE TRC Commands
ACTIVATE AR Commands
ACTIVATE ACS Commands
ACTIVATE FDS Commands
ACTIVATE WRM Commands
ACTIVATE WM Commands
ACTIVATE HABOMA Requests
ACTIVATE DISPLAY Commands
ACTIVATE INHIBIT Process Name
CMD ACTIVATE Valid Commands
THC ECLSSPER Status Data
FDS ECLSSPER Status Data
WRM ECLSSPER Status Data
WM ECLSSPER Status Data
AR ECLSSPER Status Data
ACS ECLSSPER Status Data
ECLSSPER DISPLAY Performance Data
ECLSSPER DISPLAY History Data
ACTIVATE ECLSSPER Commands
ECLSSPER HABOMA Staus Data
ECLSSPER HABOMA Performance Data
ECLSSPER HABOMA History Data
ACTIVATE ECLSSERR Commands
INHIBIT INHDATA Inhibit Process Flag
INHDATA ECLSS Inhibited Function List
INHDATA CMD Process Status
ACS ECLSSERR Failure Data
FDS ECLSSERR Failure Data
WRM ECLSSERR Failure Data
WM ECLSSERR Failure Data
AH ECLSSERR Failure Data
THC ECLSSERR Failure Data
ECLSSERR HABOMA Critical Errors
ECLSSERR STADIS Operational Data
CMD HABOMA Invalid Command
HABOMA CMD Commands
STADIS CMD Commands
THC CMD Requests
AR CMD Requests
ACS CMD Requests
FDS CMD Requests
WRM CMD Requests
WM CMD Requests

APPENDIX C - Hooks and Scars Document

Environmental Control and Life Support Systems Preliminary Hooks and Scars Document

Prepared for Brandon S. Dewberry

Information and Electronic Systems Lab
Software and Data Management Division
Systems Software Branch
Marshall Space Flight Center

by

The Johnson Research Center
The University of Alabama in Huntsville
Huntsville, Alabama 35899

Environmental Control and Life Support Systems Preliminary Hooks and Scars Document

Introduction

The Environmental Control and Life Support System (ECLSS) for the Space Station Freedom (SSF) is responsible for maintaining an inhabitable living and working environment for a crew of up to eight individuals. Since the current design is for the SSF to recycle its life sustaining substances and to dynamically handle waste products, the ECLSS has evolved into a incredibly diverse and complicated system. The ECLSS is composed of the following six subsystems: Temperature and Humidity Control (THC), Atmosphere Control and Supply (ACS), Atmosphere Revitalization (AR), Water Recovery and Management (WRM), and Waste Management (WM) (figure 1). Each of the subsystems, while defined as an separate process, must be an integral part of the total ECLSS. This requirement along with the specific needs for computer assistance with the operation of ECLSS has generated the need for a review of the current design and implementation concepts for each of the subsystems.

In April 1989, the staff of the Johnson Research Center (JRC) was contracted by NASA to begin an evaluation of each of the ECLSS subsystems to identify possible locations for additional computer software applications. Although the research effort is continuing, this report describes the software hooks and hardware scars that have been identified. Included within this report is a discussion on general considerations for expert systems and computer automation and basic communication considerations as they apply to all of the subsystems. Also included is a detailed examination of the potable water component of the WRM.

What are hooks and scars?

A <u>hook</u> is a design accommodation to facilitate the addition or the update of computer software at some point after the start of the SSF life. Thus, this research is actively searching for areas which

might not only be an immediate location for additional computer software applications, but also areas that might at sometime in the future be a viable location for some type of computer application. A scar is a hardware modification that would be required to accommodate the software hook. Since much of the actual hardware and software design is still undetermined at this time, many of the software hooks and hardware scars that are listed in this report are simply the minimal hardware requirements that a given software system would have. Therefore, many of the items identified in this report might not require additional changes to the system.

ECLSS SUBSYSTEMS

1. THC- Temperature and Humidity Control
   A. Temp & Humidity Control
   B. Avionics Cooling
   C. Process Air
   D. Thermally Conditioned Storage (TCS)

2. ACS - Atmosphere Control and Supply
   A. Pressure Control
   B. Composition Control & Monitoring
   C. Gas Storage
   D. Vent & Relief

3. AR - Atmosphere Revitalization
   A. CO2 Removal
   B. CO2 Reduction
   C. O2 Generation
   D. Trace Contaminant Control
   E. Trace Contaminant Monitor

4. WRM - Water Recovery and Management
   A. Potable Recovery
   B. Hygiene Recovery
   C. Urine Water Recovery
   D. Water Quality Monitor

5. WM - Waste Management
   A. Fecal Processing and Storage
   B. Return Waste Storage

6. FDS - Fire Detection and Suppression
   A. Fire Detection
   B. Suppressant Storage (CO2)
   C. Suppressant Distribution

Figure 1.

Knowledge Acquisition

One of the interesting tasks in developing expert systems for many of the SSF is defining the controlling parameters and rule base. Unlike most traditional expert system development arenas a large portion of SSF applications represent new technology, therefore the domain of experts to pull working background information is very limited. To aid in this process certain standard guidelines

should be incorporated into system descriptions. The following is a list of guidelines which may be helpful in the task of knowledge acquisition (KA) for the ECLSS Software Support Environment (SSE):

- SSE ought to provide standard protocols for the ways in which rules, frames and other representations should be written. Automated tools should be provided for indexing and using these elements.

- Provisions ought to be made for the characteristics that must be provided for parameters and variables in KBS.

- Documentation networks should be constructed that proceed at at least four levels. The working level of which the previous points would be a part, the experts consulted in the acquisition process and reports on the consultations, the specifications level as design is evolving and baselined, and supporting documentation

- If a CLIPS like structure is used for the final product, then hooks should be provided through which the developer can attach the relevant KA and development items to the rule base. Although no such material will be uploaded, it should be available for future development work. This becomes even more critical, if there is no standard KB development environment.

- In interview situations, a rough idea of the time window for the KB should be generated and posted in a public way. This would facilitate making informed decisions about scars.

- Given the time window decisions should be made about the use of a specialized blackboard and the use of the distributed data base. If there is a significant need for a specialized blackboard structure, then one should be developed and made part of SSE.

General Considerations

It is frequently preferable to use a commercially available software development shell to develop knowledge base systems (KBS). However presently there are only two such systems that it has been publicly announced that they will be converted into the mandated ADA programming language, CLIPS and ART. This may leave a void that will need to be filled in order to achieve the complete functionality of a satisfactory development tool. It is feasible to anticipate the future development of a totally new shell. Therefore, there are some general considerations that should be included in the SSE in order to minimize the amount of problems which could occur during KBS development and future updating by possibly differing shells. These are a sample of some of those general SSE considerations:

- A standard protocol for expressing KB elements and procedures should be developed and placed in an automated tool, ideally to be included as part of the SSE.

- A standard KB shell should be constructed for the development of KBS for SSF. It is to be recognized that in the near future the shell will have to deal with Ada, the mandated programming language. The shell should support both a development system and a run-time system. The development system will be limited to ground use. The run-time system will be available both on the ground and on the station.

- Software switches should be incorporated that allow the KBS to be switched between confirmation modes in which the user can invoke the system to confirm an action, advisor modes which presents the user with the results of the inference for confirmation, and in-the-loop modes for autonomous operation.

- The user model embedded in the KBS should be software switchable, or better self adjusting. In the early use of the system or when a new user must use the system a more instructional "flavor" should be presented to the user. As the user becomes more comfortable with the system either the system should retract instructional materials or the user should be allowed to select a more expert interface.

- Facilities for explanation should be built into the system or the shell and the level of explanation available to the user should increase as the user becomes more expert and as the system approaches in-the-loop status. The instructional and explanatory

parts of the system are inversely related. When the system approaches in-the-loop status it will be important to generate clear consistent explanations on which the user can decide whether or not to override the system.

• A KB system should provide hooks to a procedure engine if and when it is developed. A procedure engine is a software process that applies standing procedures for emergencies or maintenance to a specific circumstance. The procedure engine is in a sense an extended hypertext system.

• The KB system should be integrated cleanly into the Standard Services and database system of the station. This may require hooks both in the KB system and in the Standard Services and database software.

• Design the databases (RODBs) that service the specific units of the ECLSS software with slots for information exchange between units. For example, it should be possible to transmit information on status, diagnosis, and other inferred data from THC to WM for use in a KB at CHKSTA in POTH2O.

• Specific hooks for the KB system to tap into the information in ECLSSERR and ECLSSPER should be developed.

• Technology should not be blinded by the Ada mandate, and consideration should be given to the possibility of a LISP chip. This is especially so in KB technology since it is not unreasonable to think that research on knowledge systems will go forward in a LISP environment. If the effort is put into the use and production of more economical LISP machines, efficiency should increase while cost decreases. This will make the LISP machine look less exotic, and a potential additional processor for the Space Station.

Cooperation and communication hooks

The structural components of the ECLSS software support functions such as ECLSSERR and ECLSSPER must have access to data and message passing capabilities. This is an increasingly important and notably difficult problem since the RODB which is theoretically going to be a completely distributed onboard data base and the MODB which is at least initially going to be

ground based must be accessible from each level of the SSF software. The following items assume that there will be some CLIPS or CLIPS-like program to run the KBs.

• Specific functions should be developed to read and write to the database. The these functions should fit neatly into a rule base paradigm, so that a rule of the form:

If Read(sensor x) is greater 20,

then write(Database_name, Database_element, "caution")

The function should handle precommits, commits, and locks.

• Functions should be developed to handle failures of database transactions. For example it should be possible to write rules such that .

If Database_failure(transaction_x),

then retract(facts) and infer.

• Provisions should be made for a rendezvous between KBs or other processes. In this case one might consider a rule

If conditions a, b, c,

then rendezvous(Process_name, data_element).

• Provision should be made in the KB shell system for putting the system to sleep so that another more important task for the processor may be handled. For example,

If Impt_message,

then save(rules, facts) and sleep.

The sleep command would be designed so that the rules and facts could be reloaded and execution resumed.

• Provisions should be made so that the KB can send messages that will have greater or lesser importance. This would allow requests to be made to other processes that would force them up or down in the queue of requests.

<u>ECLSS specific hooks</u>

• The KBs in the ECLSS software environment should have access to ECLSSERR, ECLSPER, and history files.

• The KBs on the station should be constructed in such a way that they can be fit into the structure of commands, requests, and statuses.

• The KBs in ECLSS should be constructed so that where appropriate the KB in one unit can have easy access to the KBs in other units. For example, it may be appropriate for the WRM to have knowledge of how much water is being produced by THC and how much it can anticipate to have.

• In a cases where the user of the system wants to use the KBs as an assistant, appropriate modifications to DISPLAY ought to be developed to allow this.

• Since any KB software for ECLSS will be in evolution during the life of the Space Station, KBs ought to be built with an eye toward their replacement. Ideally this would mean that Run-time Knowledge Base Engines (RKBE) would be in place on the Space and Station, and that modifications can be made to the KBs on the ground. New KBs could then be uplinked to the Space Station and replace existing ones.

• Master Knowledge Bases (MKB) would be keep on the ground. Such MKBs would have access to data downlinked from the Space Station, as well as to development tools not present on the Space Station.

• Hooks to the communications systems should be developed so as to allow the efficient distribution of downloaded materials to the appropriate facility, and to provide a central facility and standardized protocol for uploading new KBs.

• Specific example 1:

CHKSTA in POTH2O gets inputs from PURIFY, STORAGE, QUALITY, and RECH2O and outputs control messages to each of these and reports status to ECLSSPER. Each of these are such that a knowledge based decision on the status of the unit may be needed. That is each of the units may vary from nominal in some way, but yet collectively be satisfactory. Each of the four units individually reports failure data to ECLSSERR. However, it should be noted that ECLSSERR only lists inputs from major subsystems, WRM in this case. The KB at the CHKSTA site might be important in terms of both horizontal and evolutionary development.

Concerning the former there are other units in ECLSS like CHKSTA. Concerning the latter what it is to be working well may change over time and the physical components being monitored may also change. If KBs can be updated like databases, then the task of updating the software for this unit will be greatly simplified. In point of fact it would simply be a case of file transfer.

- **Specific example 2:**

  WRM is another ideal candidate. It contains POTH2O, H2OQUAL, HYGH2O, URINE, and WRMLIMITS. Oddly there seems to be no centralized unit that is the WRM. However, the following points should be noticed: (1) POTH2O and HYGH2O are very closely related in terms of both software and hardware and this argues for the use of POTH2O as a site; (2) Both POTH2O and HYGH2O get information from H2OQUAL and H2OQUAL seems a natural site for a KBS; (3) The absence of a central monitor for WRM seems like either an omission or a mistake.

- **Specific example 3:**

  ECLSSERR is a good candidate for KB technology. This is especially so since the ECLSSERR will have to separate critical and non-critical errors. IN the case of ECLSERR it will be important to have the full range of communication options available, as well as a large set of the valid ECLSS commands. This latter point will become more important as ECLSS approaches in-the-loop status.

Potable Water Hooks and Scars

The potable water portion of the WRM is, based on current design, a closed loop system that extracts condensate water from THC and water from the power generation system. It is not the purpose of this report to redescribe the entire working structure of any of the ECLSS subsystems, but rather to define ways to improve the daily operations of the subsystems by suggesting locations for automated computer assistance for the SSF crew. This section addresses the hooks and scars problem from a "systems" standpoint for the potable water loop. It is basically a list of possible faults and the instrumentation that might be necessary to make an automated KBS diagnosis.

Along with the general descriptions, a more specific "hardware" oriented schematic presentation is included. This is shown as schematic diagrams. Both of the current design and as a modified design which contains specific sensors necessary for the detection of faults . The current design diagram is based on the proposed potable loop configuration in figure 2.1 of the "Phase III CMIF Water Recovery System / Facility Design Requirements" by R. Bagdigian dated 8-4-88.

(1) **Input Loads Validation:**

Currently there is no evidence of verifying the condition of input loads to the system or even if input loads are within the design specifications. It is necessary to have a rough measure of how contaminated the input stream is to successfully diagnose faults. A great deal of time may be lost attempting to fix a system producing out of spec. product water when the input load is simply too great for the system design to handle. Even if input loads are within design limits this information is essential. Consider the following scenario. The water quality monitor at the terminus of the multifiltration subsystem indicates that process water is out of spec., but only slightly. In order to diagnose and form a fault recovery plan it is necessary to know whether the system is taking heavily contaminated water and removing 99% of this contamination to produce slightly out of spec. product or is the system removing only 2% of the contaminants from fairly clean input. In the first case, recirculation might fix the problem. However, in the latter case a specific class of contaminants may have fouled a particular sorbant in the unibeds and unibed replacement might be the only solution. This information will help trend analysis and a KBS answer questions like "Are the multifiltration system unibeds needing frequent change-out due to malfunctioning prefilters (or some other hardware cause) or is it simply extremely dirty input loads?"

(2) **Leak Detection:**

Several accurate flow meters are necessary throughout the loop in order to detect leaks and blockages. Attempting to detect leaks using only the flow totalizer will result in "manual" leak detection (i.e. short circuits and wet crew).

(3) **TOC, Iodine, and Water Quality Monitor Performance:**

A sensor of another type located at the same location can often give a rough estimate of the parameter in question to aid in monitor data validation. A conductivity meter in conjunction with the iodine monitor can help assess the performance of the MCV's. A certain amount of I_2 introduced by the MCV's will exist in solution as

the ion I_3^- according to a fairly well characterized chemical equilibrium. The conductivity measured should correspond with the I_2 measurement according to the physical laws governing I_2/I_3^- equilibrium. Although other ionic contaminants would interfere to some extent, this method of validation may prove more reliable than trend analysis and more desirable both from a reliability and weigh/space saving than multiple sensor "voting".

(4) **Pumps:**

Flow and pressure sensors located immediately downstream from each pump are necessary to assess pump status (on or off) and performance. For example an ohm meter in the pump power circuit might indicate that the pump motor armature is turning and a KBS might decide that it is functioning properly when in fact a damaged impellor is not producing sufficient pressure of flow. With out this information it is impossible to assess whether a low flow/pressure condition is due to pump malfunction or line or valve blockage.

(5) **Heat Exchanger/Sterilizer Fouling:**

No temperature sensor has been included in the heat exchanger/sterilizer assembly to measure the temperature of the input stream. The delta T across the exchanger must be known in order to assess heat exchanger performance. A trend toward an increased temperature difference between input and output streams would indicate poor heat transfer and possible fouling or scale formation. Other causes would be insufficient dwell time in the exchanger due to too high a flow rate (data available from flow sensors mentioned earlier) or improper heater operation (data available from temperature sensors).

(6) **Valves:**

Several sensors in or near each control valve are necessary to report a valves condition (open or closed) in order to determine whether high pressure and/or low flow conditions are due to clogged filters, sorbants, or lines or simply a valve not in the proper condition. For instance, the controller might activate a relay to apply power to open a valve. The valve is faulty and does not open. Since the circuit is energized a conventional controller assumes the valve is open. With out valve condition verification, a KBS might conclude that some other blockage has occured. Note: this applies to any component which could be failed or blocked such as unibeds, strainers, MCV's, etc...

APPENDIX D - Dictionary

AC

Assembly complete -(used in growth configuration data book)

ACD

Architecture Control Document

ACRC

Assured Crew Return Capacity - (used in growth configuration data book)

ACRS

Advanced Carbon Reactor System

ACS

ATMOSPHERE CONTROL & SUPPLY SUBSYSTEMS

* Pressure Control
* Atmosphere Composition Control/Monitoring
* Gas Storage
* Vent and Relief

ACTIVATE

Activate Valid ECLSS Process

AES

Air Evaporation Subsystem

AI

Artificial Intelligence

AR

AIR REVITALIZATION SUBSYSTEMS

* CO_2 Removal
* CO_2 Reduction
* O_2 Generation
* Trace Contaminant Control

* Trace Contaminant Monitor

ARG
Air Revitalization Group

ATTRIBUTE
The data base model used on the space station depicts how command and data objects are named, created and how attribute information information about the objects is defined. For example, for Standard Services to read TOC sensor data into the RODB for potable water quality, Standard Services must know attribute information about addresses, conversions, and exceptions.

BACK PORCH
A truss extension on the Space Station which allows mobile servicing center access to the aft modules and provides additional structural support, depending on the module configuration.

BACKWARD CHAINING
Backward chaining is one of the ways in which a rule based system reasons. Backward chaining means that the inference engine will attempt to find the conditions that make a claim true. For example, suppose you believe that A is true, and that the system contains the following rules:
If B and C then A
if D then B.
The backward chaining process would determine that in order for A to be true B and C would have to be true. Since D would have to be true in order for B to be true the system would try to establish the truth of D and C (and generally in that order).

BMS
Bed Molecular Sieve

CELSS
Controlled Ecological Life Support System

CERV
Crew Emergency Return Capability - (used in ref. 27)

CETA
Crew Equipment Translation Aid - (used in ref 27)

CFR

Carbon Formation Reactor

CHKSTA

Monitor HYGH2O subsystem Statuses

CLIPS

CLIPS is a rule based shell for generating a knowledge based system in a C environment. C is a forward chaining system, although it can be "tricked" into a sort of backward chaining. CLIPS has strong pattern matching capabilities. As a shell, however, it has very few facilities that make life easy for the knowledge engineer. We will need to address this issue.

CMD

Verify and Validate ECLSS Commands

CMG

Control Moment Gyro - (used in ref. 27) controls Space Station guidance and navigation through active momentum management

CMIF

Core Module Integration Facility -

CSS

Customer Servicing Center - (from ref. 27) CSS is responsible for accommodating all Space Station servicing missions as will as supporting operations such as instrument and ORU storage and loading/unloading of the STS cargo bay...including accommodation, storage and servicing of the OMV, FTS, and SSRMS. Elements of the CSS include customer servicing facility, OMV, FTS, and components of the Canadian Mobile Servicing System including the mobile servicing center, SPDM, MMD, and MT.

DDT&E

Design, Development, Test, and Engineering.

DISPLAY

ECLSS Display

DMS

DMS is the distributed database management system. DMS services can be divided into Data Management Services, Application Communication Services, Application Execution Services, and User Support Environment Services.

ECLSS

Environmental Control and Life Support Systems

ECLSSERR

ECLSS Fault Detection and Isolation

ECLSSMGR

ECLSS Manager, formerly ECLSS Support Software

ECLSSPER

ECLSS Performance and Trend Analysis

EDC

Electrochemical Depolarization Cell

EDMT

EXTENDED DURATION METABOLIC TEST

Complete closure of the water loop will be addressed for the first time during the EDMT. Reclaimed hygiene water will be reused by test subjects for showers and handwashing. Additionally , subjects will ingest reclaimed potable water on a limited basis.

ELV

Expendable Launch Vehicles - (from ref. 27)

EMM

Evolution Mission Model - (used in ref. 27)

EPS

Electrical Power System

ES

Expert System

ESA

European Space Agency - (used in ref. 27)

ESSTAP

Emulation, Simulation, Sizing, and Technology Assessment Program. NASA's attempt to quantify the benefits that can be derived when an early emphasis is placed on software tools. Benefits expected are shortened development cycles, improved performance and resultant lower costs. The JRC's ECLSS-KBS project is a part of this broad program.

EVA

Extravehicular Activity - (from ref. 27)

EVAS

Extravehicular Activity Systems - (from ref. 27)

EVOLUTION GROWTH BLOCK

A group of incremental growth steps for several Space Station systems that will provide an overall, complementary increase in the Space Station's resources and capabilities.,

FDIR

Failure Detection and Recovery

FDS

FIRE DETECTION AND SUPPRESSION SUBSYSTEMS

* Fire Detection
* Suppressant Storage
* Suppressant Distribution

FORWARD CHAINING

Forward chaining is one of the ways in which a rule based system reasons. Forward chaining means that the inference engine will use new true claims and its rules to infer another true claim. For example, suppose that the system contains the following rules:

If B and C then A

if D then B.

The forward chaining process would do nothing until a fact was asserted. If D is asserted then B would be inferred, and if C had already been asserted then A would be concluded. Alternatively if B were asserted and C had already been asserted A would again be inferred.

FTS

Flight Telerobotic Servicer - (from ref. 27)

H2OQUAL

Process Water Quality Sensor Data

HAB

Habitation

HABOMA

Habitat Operations Management Applications

HAD

Heat Acquisition Device - (from ref. 27)

HEPA

High Efficiency Particulate Air

HYGH2O

Process Hygiene Water

IESP

Expert System Project

INCO

Integrated Communications Officer

INHDATA

Inhibited Function List

INHIBIT

Process ECLSS Inhibit Commands

ISP
Inter -vehicular Activity - (from ref.27)

IWWMS
Integrated Waste & Water Management System

JSC
Johnson Space Center

KB
knowledge based

KBS GROUP
Group of KB systems experts enlisted by NASA Space Station Level I Strategic Plans and Programs Division

KNOWLEDGE
Knowledge is stored in some representation and is used to direct the addition or deletion of elements from some fact base. Rules are a typical representation for knowledge. For example, a rule might claim that if the TOC is greater than a specified number, then shut down the process and notify the supervisor.

KOH
Potassium Hydroxide

LAB
Laboratory

LAN
local area network

LARC
Langley Research Center - (from ref. 27)

MCV

Microbial Check Valve

Not really a valve as it doesn't control fluid flow. Rather, it is supposed to control the "flow" of microorganisms. Consists of a resin bed which provides about 2 ppm iodine to process waters for bacteriostasis.

MF

Multifiltration

MMD

Mobile Maintenance Depot - (from ref. 27)

MMPF

Microgravity and Materials Processing Facility - (from ref. 27)

MODB

MODB is the master object database manager. The MODB allows information about a devices MDM address, Engineering unit conversions, and exception condition parameters to be predefined into a configuration managed database that can be sent to a node. The MODB manager uses the predefined object and attribute information to build the RODB that allows Standard Services to configure its services to match the actual configuration of sensors, effectors, and derived data and command objects.

MRDB

Mission Requirement Data Base - (from ref. 27)

MSC

Mobile Servicing Center - (from ref.27)

MSFC

Marshall Space Flight Center

MSS

Mobile Servicing System - (from ref. 27)

MT

Mobile Transporter - (from ref. 27)

NSTS

National Space Transportation System - (from ref. 27)

OMA

Operations Management Applications

OMGA

Operations Management Ground

OMV

Orbital Maneuvering Vehicle (from ref. 27)

Proposed vehicle to boost Shuttle payloads to geosynchronous orbit. The vehicle would be based and serviced at the space station.

ORU

Orbital Replacement Units - (from ref. 27)

OXONE

OXONE - (tm) DuPont Corp.

Proprietary dry chemical oxidizing compound, for industrial chemical synthesis.Active ingredient is Potassium monopersulfate. The active ingredient cannot be isolated in pure form so oxone is a mixture of KSO3,KHSO4, and K2SO4. Aqueous solutions oxidize via a free radical mechanism possibly involving O. , X., and/or peroxydisulfuric acid.

PATTERN MATCHING

Pattern matching in knowledge based systems most often refers to the patterns of truth in the facts and rules of the system and the flexibility of their being matched. For example, suppose there is a term (T) that takes three arguments (a,b,c). Suppose that T(a b c) is true. One might only care about the value of one of the arguments, say b. Or again one might be interested in the values of two of the arguments, say a, c. A system with good pattern matching abilities would allow you to match in many ways, while weak pattern matching would allow only one way.

POTH2O

Potable Water

PURIFY

Monitor and Control the Purification Process

PVP

Polyvinyl Pyrolidine

PWMFS

POTABLE WATER MULTIFILTRATION SYSTEM

Used to recover potable grade water from a mixture of humidity condensate, CO2 reduction by-product water, and CO2 removal steam condensate. Consists of a system of 5 "Unibed" resin cartridges, pump, heat exchanger/sterilizer, and sensors.

QCM

Quartz Crystal Microbalance

QUALITY

Monitor the Water Quality

R&D

Research and Development

RECH2O

Monitor and Control Receiving Tank and Pump

RMOAD

Reference Mission Operational Analysis Document- (from ref. 27)

RO

Reverse Osmosis

RODB

The Runtime Object Data base can be thought to exist at each node of the DMS. The RODB will contain the current values values for all currently available sensor and derived data item that originate at that node. Standard Services will provide location-transparent access to data in remote RODB's via directories built by the MODB manager. Sensor and derived data are written to the

RODB by the data supplier, and sensor and derived data can be read out of the data base by the users of the data.

RULE

Rules are one of the schema used to represent knowledge. A rule is composed of a left hand part that contains the conditions, and a right hand part that contains the actions. In forward chaining when the conditions are satisfied the actions are performed. In backward chaining if the goal matches an assertion of fact in the action side the engine will attempt to determine a value for the conditions.

SAWD

Solid Amine Water Desorbed

SD

Solar Dynamic - (from ref. 27)

SDMS

The Standard Services Data Management Services interfaces support applications access to the SSIS relational databases, SSIS files, and SSIS shared memory resident objects. It provides the services of a general purpose DBMS, including retrieve, add, change, and delete operations on single record or multiple records at a time. The on board DBMS will mange a centralized data base distributed across a network.

Data base services include:

LOGON, OPEN, SQL, DESCRIBE, NAME, DEFINE, BIND, EXECUTE, FETCH, COMMENT, COMMITOFF, COMMIT, COMMITON, ROLLBACK, ERRORMSG, CLOSE, LOGOFF, OPTIONS, RESUME.

File management services include:

CREATE, OPEN, CLOSE, DELETE, RESET, READ, WRITE.

SFE

Static Feed Electrolyzer

SPDM

Special Purpose Dextrous Manipulator - (from ref. 27)

SPE

solid Polymer Electrolyte

SSAA
space station advanced automation

SSDA
Standard Services Data Acquisition provides both data and command functions. SSDA reads all sensor data that is defined on the local bus, and optionally converts raw data to Engineering units, saves values to RODB, and performs standard data processing services. SSDA also performs 1553 bus I/O to MDM attached effector devices. Data acquisition is table driven. The tables can be considered to be in the RODB as built by the MODB manager.

SSE
Software Support Environment

SSRMS
Space Station Remote Manipulator System - (from ref. 27)

STADIS
Station Distributed System

STANDARD SERVICES
Standard Services provides data and command services for onboard core and payload systems. In this context data refers to sensor data, ADA application data, and UIL data. The last two items are called derived data. Commands refers to effector commands, requests to ADA application programs, and requests to UIL procedures. Standard Services allows local application programs to modify online some of the attribute information such as Engineering units or exception limit parameters of existing objects.

STORAGE
Monitor and Control Potable Water Storage

STS
Space Transportation System - (from ref. 27)

STV

Space Transfer Vehicle - (from ref. 27)

SWRS

Shower Water Recovery System

TBD

To Be Determined - (from ref. 27)

TBS

To Be Supplied - (from ref. 27)

TCCS

Trace Contaminant Control Subsystem

TCS

Thermal Control System - (from ref. 27)

THC

TEMPERATURE / HUMIDITY CONTROL SUBSYSTEMS

* Temp./Humidity Control
* Avionics Cooling Air
* Process Air
* Thermally Conditioned Storage

TIMES

Thermoelectric Membrane Evaporator System. Alternate to VCD for recovery of hygiene grade water from pretreated urine.

TMP

Trial Payload Manifest - (from ref. 27)

TOC

Total Organic Carbon

TRRJ

Thermal Radiator Joint - (from ref. 27)

TSA

Test Support Accessory

UIL

UIL is the User Interface Language for the DMS.

UNIBED

Trade name for a commercial sorbents/exchange resin bed used to post-treat sterilized humidity condensate and CO2 process water as a potable supply. 26.25" X 2.25" dia.

Sorbent Media

(in order of flow)

MCV-H	96 g.
IRN-77	90 g.
IRA -68	60 g.
580-26	600 g.
APA	95 g.
XAD-4	90 g.
IRN-150	90 g.
MCV-H	97 g.
IRN-77	90 g.

URINE

Process Urine

VCD

VAPOR COMPRESSION DISTILLATION

The VCD subsystem is a candidate subsystem (along with the TIMES) for recovery of hygiene grade water from a pretreated urine/flushwater mixture. Subsystem operates on vacuum distillation principles.

VPCAR

Vapor Phase Catalytic Ammonia Removal

WCS

Waste Collection System

WM

WASTE MANAGEMENT SUBSYSTEMS

* Fecal Processing & Storage
* Return Waste Storage

WP -01

Work Package 01 - (from ref. 27)

WRM

WATER RECOVERY AND MANAGEMENT SUBSYSTEMS

* Potable Recovery
* Hygiene Recovery
* Urine Water Recovery
* Water Quality Monitor

WRMLIMITS

WRM Limit Data

WRMLMT

Set WRM Limits

APPENDIX E - Report Software Description and Instructions

The software that is to distributed with some of the reports is contained on two Macintosh™ diskettes.

Diskette 1 contains the text of this report and many of the diagrams. The text is formatted for the Microsoft Word™ 4.0 word-processing software.

Diskette 2 contains two HyperCard™ stacks: Flows and Dictionary.

The Flows stack contains a representation of the context flow diagrams that lead to the potable water subsystem. The stack can be started in the usual way, and all normal HyperCard™ functions are available. At the first card clicking on either the ECLSS Software Support unit or the WRM unit will take the user to the next card. Flows for the other parts of the ECLSS have not been implemented. The remaining cards contain a representation of the software unit in terms of inputs/process/outputs. Clicking on any output term, takes the user to that output. In this way the user can trace the output. On many of the cards there is a "DETAIL" button above the process description. Clicking on this button presents the user with a more detailed account of the process. The process is again represented in input/process/output style, and clicking on the output term allows the user to trace the output. All of the text fields are unlocked and can be modified by the user.

The Dictionary stack is a general dictionary stack with the ability to delete terms turned off. The Dictionary stack contains all of the terms in the dictionary section of this report. The stack can be started in the usual way. The stack has several ways in which the information can be accessed. Double clicking on any word or dragging on phrase in the entries selects it from the index. Click the FIND button to go to the card. When you are in a dictionary card selecting a word or phrase and clicking the REFERENCE button puts that word or phrase into the reference field of the main card. It can then be selected as any other item in the index field. While in a dictionary card, use the MAIN CARD button to return to the main card. Terms can also be browsed by first letter. Clicking on an alphabet button takes the user to the first dictionary card that begins with that letter.

ADD TERM brings up a dialogue that leads a user to the addition of a new term. WRITE sends the dictionary to an ASCII file for later processing. CLEAR removes the dictionary and compacts the stack. BUILD creates the dictionary stack from a file previously saved by a WRITE. This allows the user to maintain several dictionaries. Only one dictionary is included with this stack.

In the Dictionary stack all of the fields are unlocked and indexes are maintained automatically. Altering the Dictionary Entries field directly will corrupt the index!

The diskettes with these materials have been supplied to the following:

Jim McKee — University of Alabama in Huntsville
Dan Rochowiak — University of Alabama in Huntsville
Brandon Dewberry — Marshall Space Flight Center.

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